

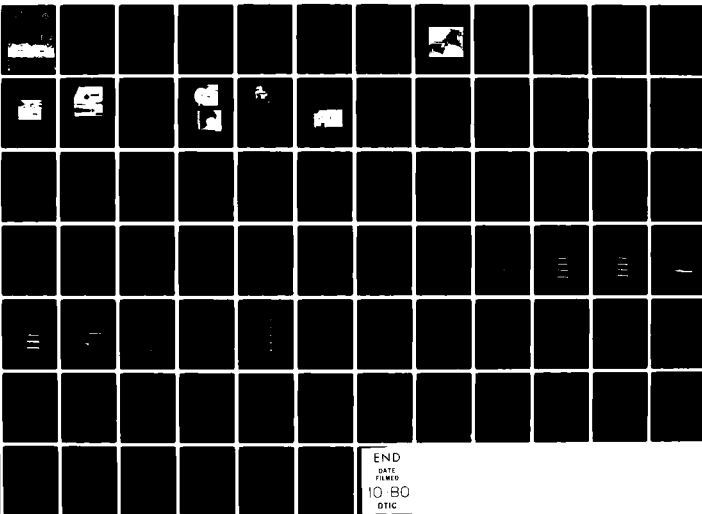
AD-A088 896

ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/G 13/13
PROTOTYPE FILLING AND EMPTYING SYSTEM MEASUREMENTS, NEW BANKHEA--ETC(U)
AUG 80 A R TOOL
WES/TR/HL-80-13

UNCLASSIFIED

NL

1 of 1
AD-A088 896



END
DATE
FILMED
10 80
DTIC



LEVEL ¹²

12



TECHNICAL REPORT HL-80-13

PROTOTYPE FILLING AND EMPTYING SYSTEM MEASUREMENTS, NEW BANKHEAD LOCK BLACK WARRIOR RIVER, ALABAMA

by

Allen R. Tool

Hydraulics Laboratory

U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

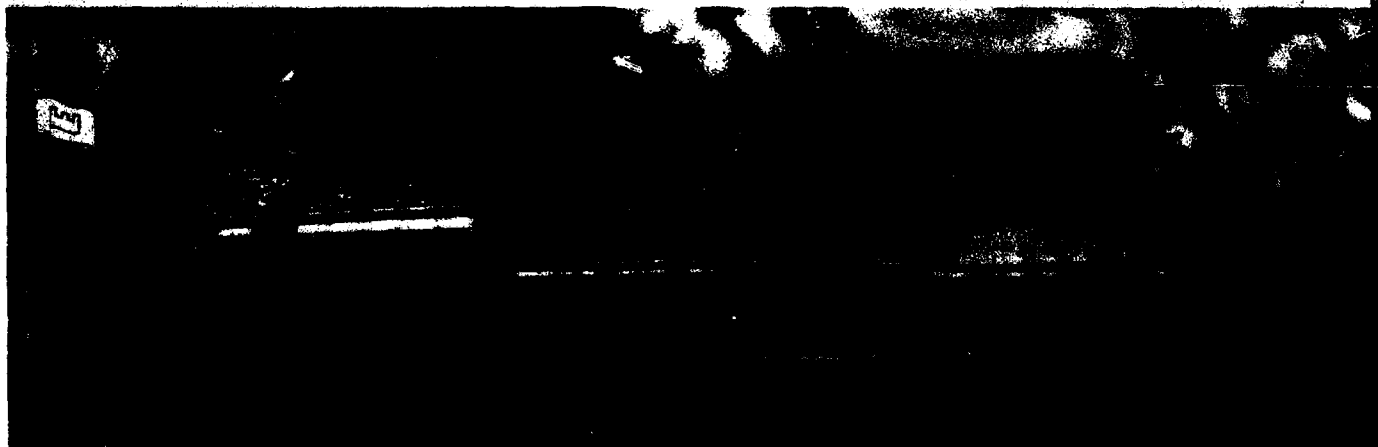
August 1980

Final Report

Approved For Public Release; Distribution Unlimited

DTIC
ELECTE
SEP 10 1980
A

AD A088896



Prepared for U. S. Army Engineer District, Mobile
Mobile, Ala. 36628

DDC FILE COPY

80 9 10 030

**Destroy this report when no longer needed. Do not return
it to the originator.**

**The findings in this report are not to be construed as an official
Department of the Army position unless so designated
by other authorized documents.**

**The contents of this report are not to be used for
advertising, publication, or promotional purposes.
Citation of trade names does not constitute an
official endorsement or approval of the use of
such commercial products.**

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

14 WES/TR/HLI-80-13

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report HL-80-13 ✓	2. GOVT ACCESSION NO. AD-A088 896	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROTOTYPE FILLING AND EMPTYING SYSTEM MEASUREMENTS, NEW BANKHEAD LOCK, BLACK WARRIOR RIVER, ALABAMA	5. TYPE OF REPORT & PERIOD COVERED 9 Final report	
7. AUTHOR(s) 10 Allen R. Tool	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Hydraulics Laboratory P. O. Box 631, Vicksburg, Miss. 39180	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 12 901	
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, Mobile P. O. Box 2288 Mobile, Ala. 36628	12. REPORT DATE 11 Aug 1980	13. NUMBER OF PAGES 84
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified	
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE		
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Hydraulic models Prototypes John Hollis Bankhead Lock Water pressure measurement Lock filling and emptying system Locks (Waterways) Prototype tests		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Prototype studies were conducted to measure pressures in the filling and emptying culvert system and to monitor various other parameters relating to the operation of the new John Hollis Bankhead Lock. Air demand downstream of the filling valve was studied as related to low pressures in the culvert. Measurements at some points in the culverts indicate that pressures existed at or near the vapor pressure of water for certain test conditions. (Continued)		

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

11/13/81

JCE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (Continued).

Prototype data are compared with math model computations for piezometric head downstream of the filling valve, valve well water-surface elevation, and lock water-surface elevation. This comparison revealed generally good agreement.

Unclassified

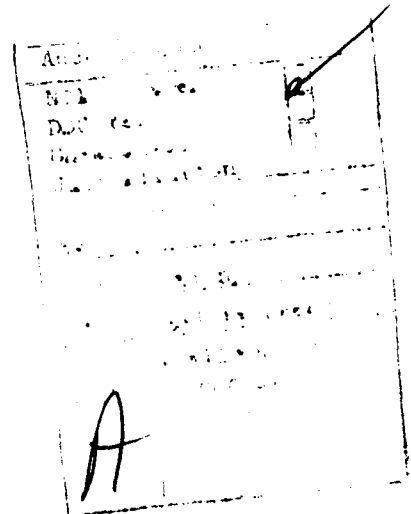
SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

PREFACE

The hydraulic prototype tests presented in this report were performed under the sponsorship of the U. S. Army Engineer District, Mobile. The tests were accomplished by the Prototype Branch, Hydraulic Analysis Division, of the Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES).

Mr. A. R. Tool, hydraulic engineer, was WES project engineer for the tests; individuals of the Mobile District contributed substantially to the completion of the tests. This report was prepared by Mr. Tool with the assistance of Dr. F. M. Neilson under the supervision of Mr. E. D. Hart, Chief of the Prototype Branch; Mr. E. B. Pickett, former Chief, and Mr. M. B. Boyd, present Chief of the Hydraulic Analysis Division; and Mr. H. B. Simmons, Chief of the Hydraulics Laboratory.

Commanders and Directors of WES during the conduct of the study and the preparation and publication of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.



CONTENTS

	<u>Page</u>
PREFACE	1
CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)	
UNITS OF MEASUREMENT	3
PART I: INTRODUCTION	4
Pertinent Features of the Project	4
Purpose of the Study	6
PART II: MEASUREMENTS, EQUIPMENT, AND PROCEDURES	8
Measurements and Equipment	8
Recording System	13
Test Procedures	15
PART III: DATA REDUCTION AND ANALYSIS	17
Data Reduction	17
Analytical Model of Lock Operation	19
Data Analysis	20
PART IV: CONCLUSIONS	33
Culvert Pressures	33
Air Demand	33
Model-Prototype Comparison	33
TABLES 1 and 2	
PLATES 1-23	
APPENDIX A: HYDRAULICS OF THE CULVERT SYSTEM	A1
Introduction	A1
Relative Efficiencies	A3
Equations Describing Lock Filling	A6
Data Reduction - L_m	A9
Overall Loss Coefficient	A9
Distribution of Losses in the System	A13
Overtravel	A22
Conclusions and Recommendations	A22
APPENDIX B: NOTATION	B1

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
cubic feet per second	0.02831685	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per second	0.3048	metres per second
feet per second per second	0.3048	metres per second per second
inches	25.4	millimetres
inches per second	25.4	millimetres per second
miles (U. S. statute)	1.609344	kilometres
miles per hour (U. S. statute)	1.609344	kilometres per hour
pounds (force) per square inch	6894.757	pascals
square feet	0.09290304	square metres
square inches	645.16	square millimetres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

PROTOTYPE FILLING AND EMPTYING SYSTEM MEASUREMENTS

NEW BANKHEAD LOCK, BLACK WARRIOR RIVER, ALABAMA

PART I: INTRODUCTION

Pertinent Features of the Project

1. The new John Hollis Bankhead Lock (Figure 1) is on the Black Warrior River 30 miles* southwest of Birmingham, Alabama (Figure 2).

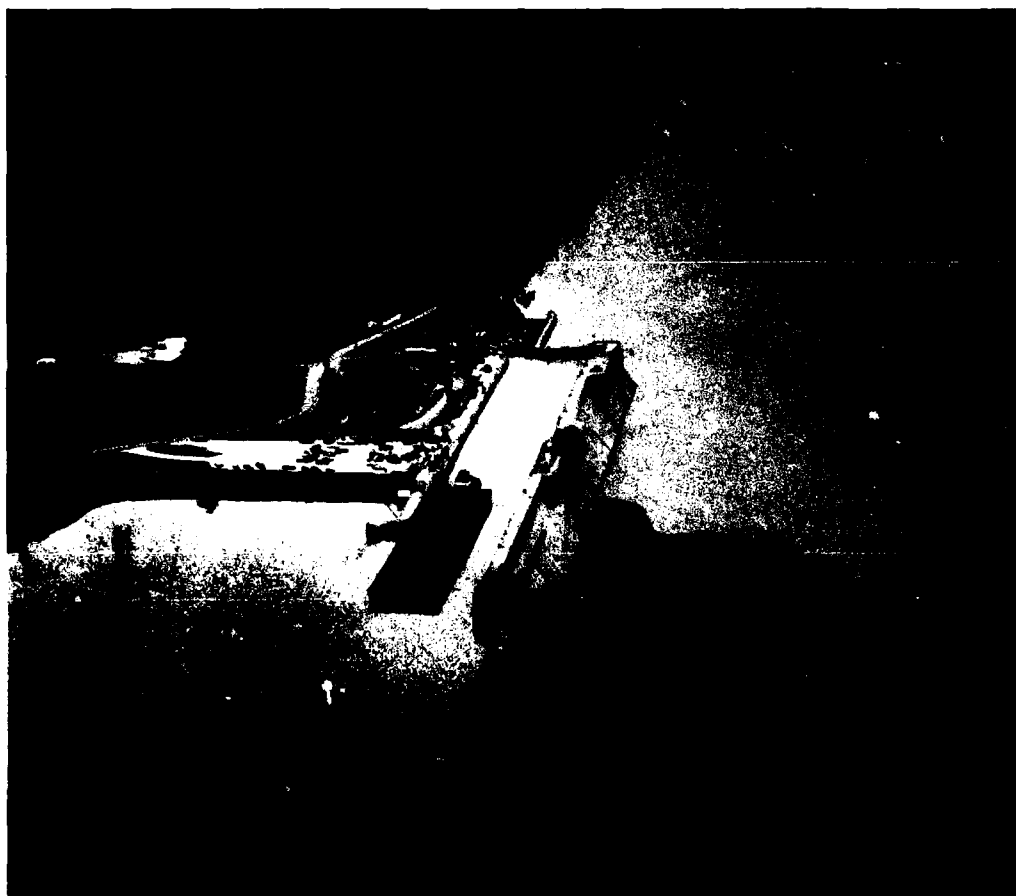


Figure 1. John Hollis Bankhead replacement lock

* A table for converting U. S. customary units of measurement to metric (SI) units is given on page 3.

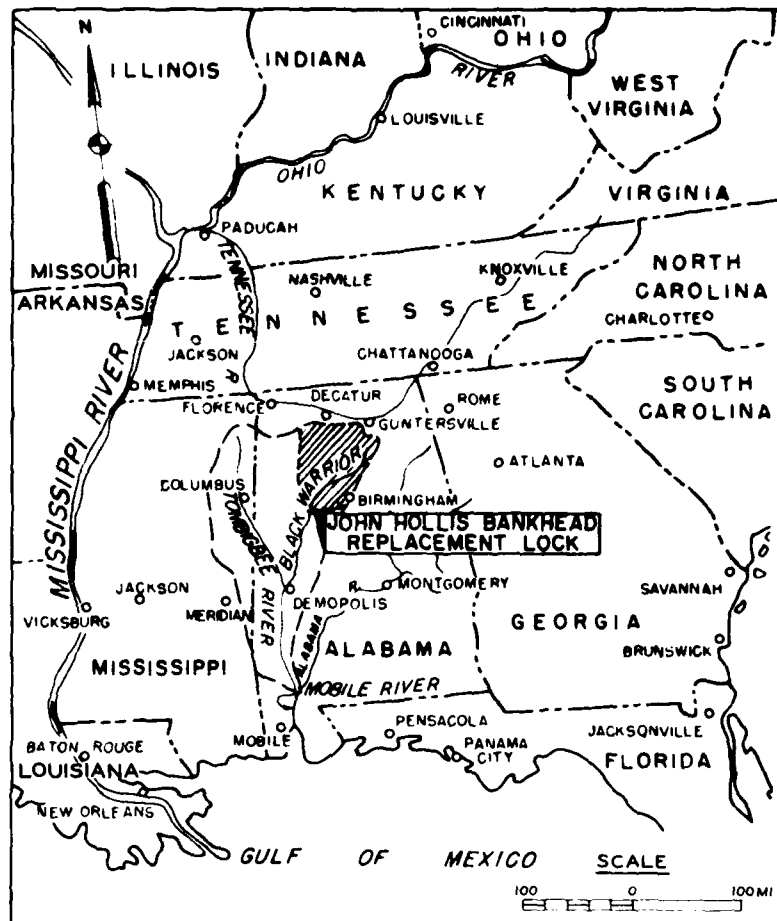


Figure 2. Vicinity map

2. Bankhead Lock has a maximum design lift of 69 ft and a usable chamber of 110 ft by 600 ft. Pertinent details of the lock design are shown in Plate 1. The filling and emptying system consists of 10-port intake manifolds on both upstream walls; 14- by 14-ft culverts with filling and emptying valves of the same size; a lateral crossover culvert and "tuning fork" culvert bifurcation section in the center of the lock chamber to provide equal distribution of flow from either one or both culverts to the four 10- by 12.5-ft longitudinal floor culvert manifolds; and a discharge basin for both culverts on the riverside of the lock. The flow is distributed into the chamber through a total of ninety-six 3.5- by 1.5-ft ports. To improve pressure conditions

during filling, a splitter pier was installed in each culvert near the crossover section as shown in Plate 1.

3. Model studies of the lock* were conducted by the U. S. Army Engineer Waterways Experiment Station (WES) on a 1:100-scale general model, which reproduced the river for approximately 1.5 miles upstream and downstream from the lock, and a 1:25-scale model of the filling and emptying system. The subject prototype tests were conducted in July 1976 by WES with the assistance of the U. S. Army Engineer District, Mobile.

Purpose of the Study

4. A physical model of a lock normally is less efficient than the prototype--that is, the prototype fills and empties in less time than the model predicts. Because of higher lifts (and greater velocities) in some proposed lock designs, extreme pressures within the culverts must be predicted more correctly than by direct extrapolation from the model. One proposed method of doing this is by incorporating hydraulic-friction corrections to the model data by numerically integrating the differential equations that describe lock operation. Consequently one objective here is to look at the reliability of constant coefficients as far as the prototype is concerned. The approach is simply to evaluate fewer coefficients and to perform the integration for various boundary conditions set up during the course of the field study--the purpose being to determine whether or not the present analytical description of lock operation is complete enough so that it is, at least, a promising tool as far as the extrapolations of future model tests are concerned. The approach is discussed in more detail in Appendix A of this report.

5. Of course the major interest in the study concerns items that are sensitive to lock operation situations; data concerning these items

* N. R. Oswalt, J. H. Ables, Jr., and T. E. Murphy. 1972 (Sep). "Navigation Conditions and Filling and Emptying System, New Bankhead Lock, Black Warrior River, Alabama; Hydraulic Model Investigation," Technical Report H-72-6, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

are used for establishing guidelines for lock operation procedures. Specific interests are: cavitation in the culverts during emptying, air venting below the filling valves, valve hoist loads, maximum draw-down in the upstream lock approach, vibration and pressure fluctuations, and floor-culvert roof pressures.

PART II: MEASUREMENTS, EQUIPMENT, AND PROCEDURES

Measurements and Equipment

6. Locations and details of the instruments used are shown in Plate 1 and Table 1; the measurement program is discussed in the following paragraphs.

Water surfaces

7. Static water-surface elevations were observed in the upstream and downstream pools and in the lock chamber before and after each lock operation. In addition, the upper pool elevation was continuously recorded to measure surges occurring in the upstream approach channel. Staff gages were used upstream and downstream of the structure and in the lock chamber for static conditions. A float-actuated water-level recorder on the upstream river guide wall was used to measure surge heights in the approach channel.

8. The piezometric head in the upstream and downstream river valve wells (UVW and DVW in Table 1 and Plate 1) was measured using 50-psia pressure transducers. These transducers and their watertight adapters were located inside perforated pipe sections for protection. The pipe sections were secured to grease lines on the valve well wall at elevations below minimum water levels.

9. Lock chamber water-surface elevation during operation was measured by two methods: (a) using a 50-psia transducer (LWS1) mounted in a perforated pipe similar to Uvw and DVW and fastened with hose clamps to a rung of a recessed ladder in the river wall of the lock chamber; and (b) by determining the vertical position of a floating mooring bitt and the water surface relative to the mooring bitt. To accomplish this, a machined 1.000-ft-circumference aluminum pulley and a small V pulley were mounted over the mooring bitt at the top of the lock wall (Figure 3). A fine steel cable attached to the bitt was wrapped once around the machined pulley and draped over the small pulley with the end attached to a suspended weight. The shaft of the 1-ft-circumference pulley was mated to the shaft of an angular potentiometer

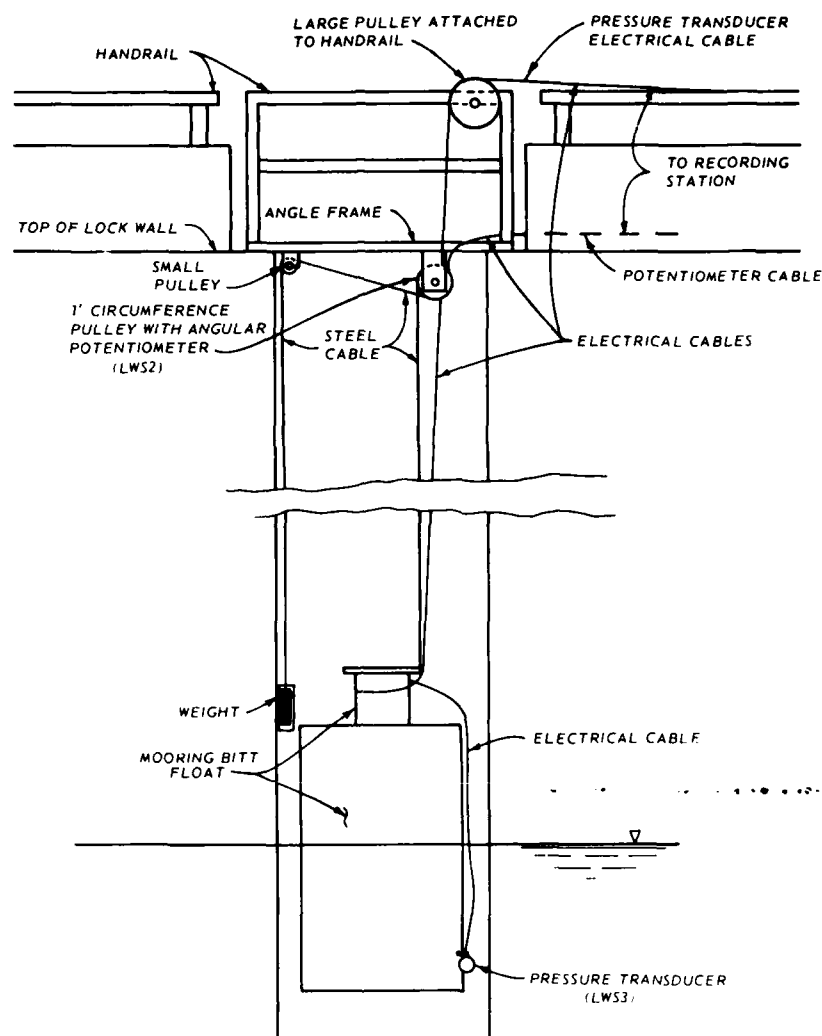


Figure 3. Lock water surface indicating apparatus at top of floating mooring bitt slot in lock wall

(LWS2). With this arrangement any vertical movement of the mooring bitt caused a rotation of the machined pulley, which was detected electrically as a rotation of the potentiometer (360 degrees rotation equaling 1.000 ft vertical movement). A 25-psia pressure transducer was mounted below the water level on the mooring bitt in a perforated pipe section (LWS3). This transducer was used to measure pressure changes due to variations in submergence of the mooring bitt and thereby the instantaneous water surface relative to the bitt. The maximum expected precision

of the combination of the two devices, LWS2 and LWS3, is in the order of ± 0.01 ft for displacements less than about 2 ft; for larger displacements (up to maximum lift) the accuracy is substantially poorer because of accumulative errors (cable stretch, slippage, etc.). The overall accumulative error during a test is known by comparison with static water levels; when required, this error (always less than 0.01 ft/ft) was distributed linearly with regard to elevation. Of course, the error in relating this local rate-of-rise measurement to flow rate is uncertain because of water-surface oscillations--the ± 1 percent uncertainty level is the best that could be achieved with no oscillations.

Piezometric pressures

10. As listed in Table 1 and located in Plate 1, dynamic pressures were recorded on the side of the culvert (TV1) and in the sealed bulkhead slot (TB1) immediately downstream of the river-wall filling valve; in the wall of the emptying culvert near the river-wall splitter pier (TC1); and in five locations (TL1, TL2, TL3, TL4, TL5) in the chamber floor culverts.

11. The pressures were measured using 50- and 100-psia unbonded strain gage transducers. A 100-psia transducer (TV1) was flush-mounted 12.8 ft downstream of the filling valve and 7.9 ft above the invert of the river-wall culvert. For installation the transducer and its mounting device were secured in the end of a pipe section; divers in the chamber then extended the complete assembly through a hole drilled through the chamber wall. To install the 50-psia transducer (TB1) and its watertight adapter in the bulkhead slot a vertical hole was drilled and tapped through the bulkhead seal. The 100-psia transducer (TC1) installed near the river-wall splitter pier at sta 3+50.7A, el 169.4,* was near the point of tangency of the river-wall emptying culvert and the curved portion of the crossover culvert; this transducer was mounted and installed in the same manner as TV1. The five 50-psia pressure transducers (TL1, TL2, TL3, TL4, TL5) installed in the roof of the floor

* All elevations (el) cited herein are in feet referred to mean sea level (msl).

culvert system were mounted flush with the roof of the culvert at el 169.0 in a fashion similar to TV1 and TC1.

Valve movement

12. Movement of any operating tainter valve(s) was monitored for the duration of each test. The measuring devices were angular potentiometers (UVL, UVR, DVL, DVR) attached to the remote indicator unit such that any valve movement (opening or closing) caused a rotation of the potentiometer (Figure 4).

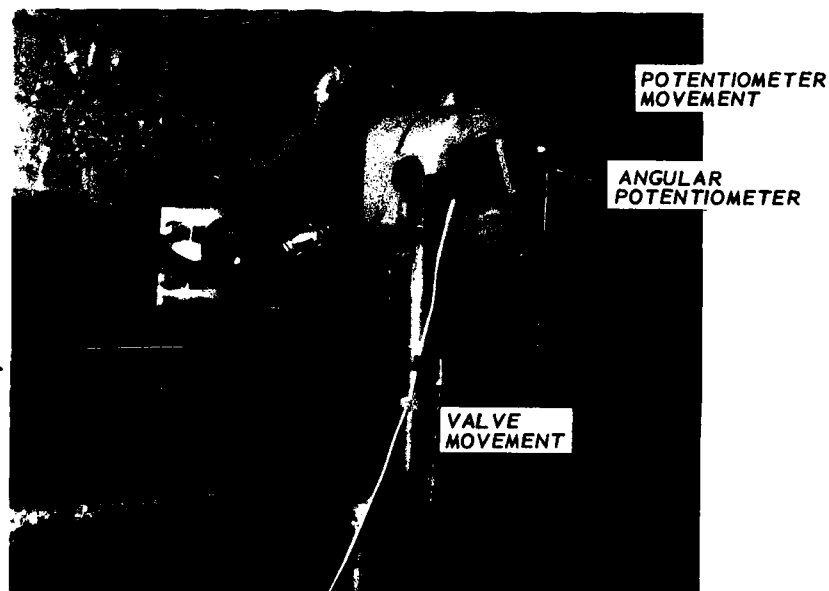


Figure 4. Tainter valve movement indicator

Valve hoist load

13. Pressures in the operating cylinder of the river-wall filling valve were continuously monitored for the duration of each filling test. Prior to selected tests, the static pressures in the valve cylinder hydraulic system were read from Bourdon gages and recorded. One 2000-psi pressure cell (VPB) measured hydraulic pressures on the raising side of the piston; an identical cell (VPF) measured the pressures on the lowering side of the piston (Figure 5).

Miter gate opening

14. Movement of the miter gates caused by overfilling (upstream

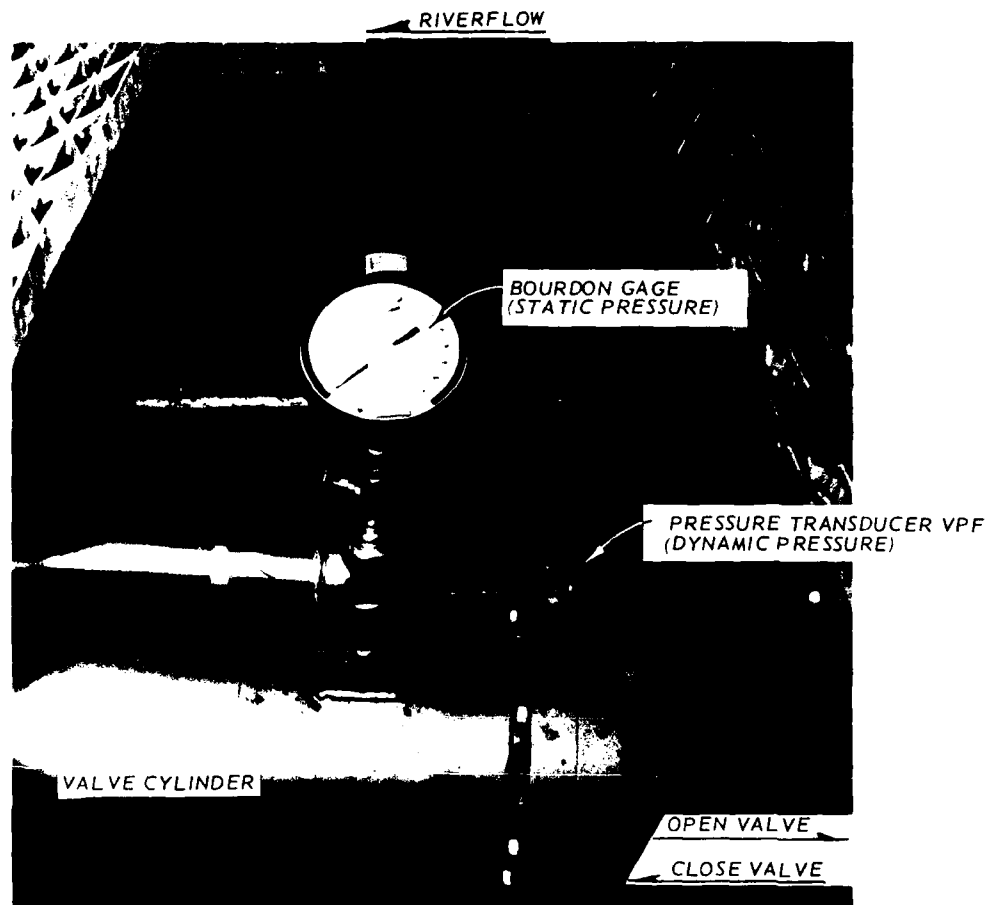


Figure 5. Valve hoist cylinder, pressure gage, and transducer

gates) or overemptying (downstream gates) was monitored in order to obtain the time at which initial opening occurred and the total arc of opening. Angular potentiometers (GUL, GUR, GDL, GDR) were mounted at the point of rotation of each miter gate such that any movement of the gates was monitored continually during each test (upper gates during filling, lower gates during emptying). Microswitches (USS, DSS) were mounted on the mating edges of each pair of upstream and downstream, respectively, miter gates to record the time of initial gate opening.

Filling valve air demand

15. The velocity of air drawn by the two 12-in.-diam air vents at the river-wall filling valve was monitored continuously with respect to

time (AV1, AV2). A 6-ft-long by 11.5-in.-ID pipe extension and bell mouth (Figure 6a) were attached to each of the two air vents and a two-way pitot tube, AV2 (Figure 6b), was mounted 1.0 ft from the bellmouthed entrance in the center of each extension. The differential pressures at the pitot tubes were recorded using ± 1.0 -psid pressure transducers. Air flow in each vent was controlled by a 12-in. wedge gate valve.

Structure vibration

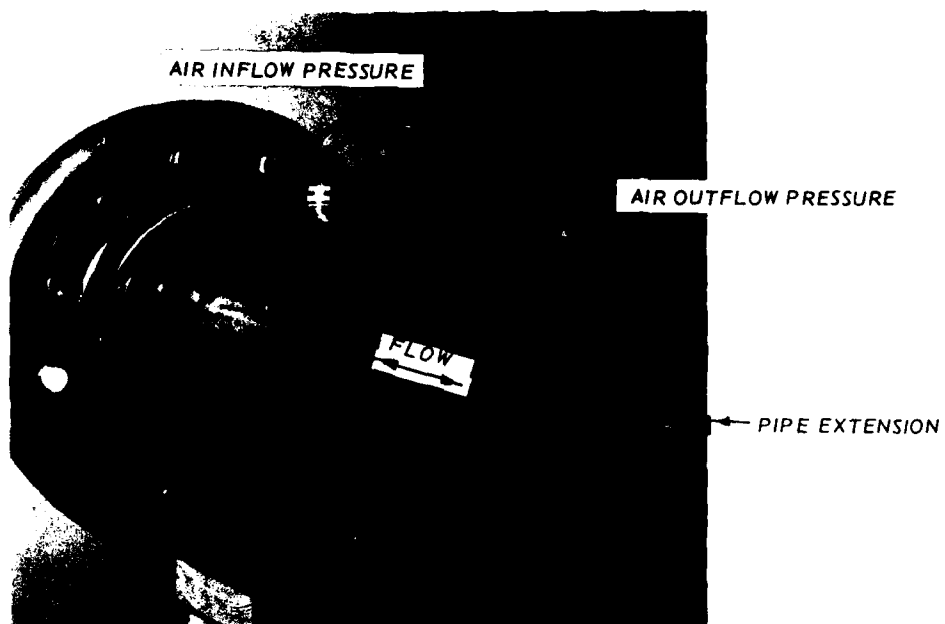
16. Acceleration measurements were made to determine the amplitude and frequency of structural vibration. An Endenco piezoelectric accelerometer, TS1 (Figure 7), was attached to the river-wall gallery floor above and just downstream of the crossover culvert as shown in Plate 1.

Meteorological conditions

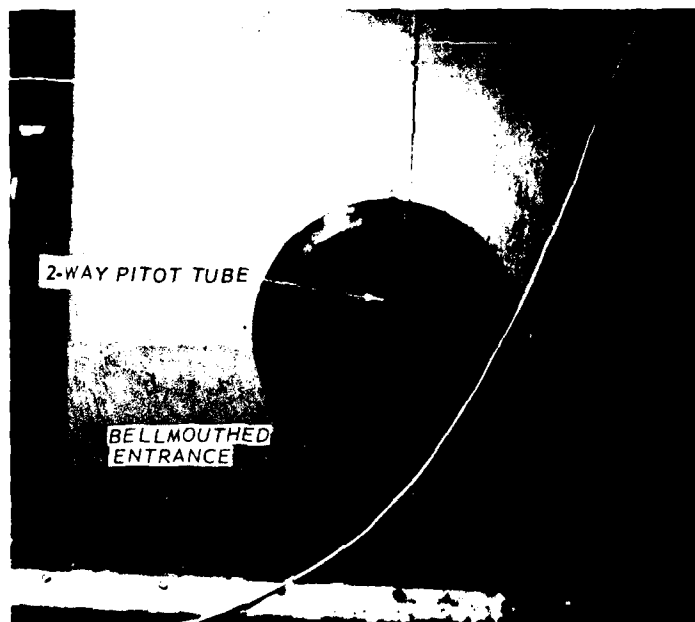
17. Weather conditions and water temperature were recorded throughout the test program. The parameters measured were air and water temperature, and wind speed and direction. These data are included in Table 2. A portable weather station was placed in a flat open area near the lock for recording most of this information.

Recording System

18. A schematic and photograph of the recording system are shown in Figure 8. Briefly, the system consisted of two each of the following: (a) WES-fabricated model 01 amplifier to condition the incoming transducer signals (an independent Kistler Model 503 charge amplifier was used with the accelerometers); (b) Sangamo Model 3500, 14-channel, frequency-modulated, magnetic tape recorder with frequency responses up to 2.5 kHz at 7.5 in./sec (ips) and 20 kHz at 60 ips; (c) Century Model 541 galvanometer driver to supply higher current to the high-frequency galvanometer; and (d) CEC Model 1-119, 12-in. chart, oscillograph capable of reproducing 36 channels of data at a paper speed from 0.25 ips to 160 ips at a frequency response of 0-2500 Hz. The tape and oscillograph speeds used for recording the Bankhead data were 7.5 ips and 0.25 ips, respectively. Channels of each recorder were used for a voice recording, event mark, and a timed pulse (for correlating data from the two recorders).



a. Air vent extension and two-way pitot tube leads
(downstream view from backside of bell mouth)



b. Looking into bellmouthed entrance

Figure 6. Air vent extension

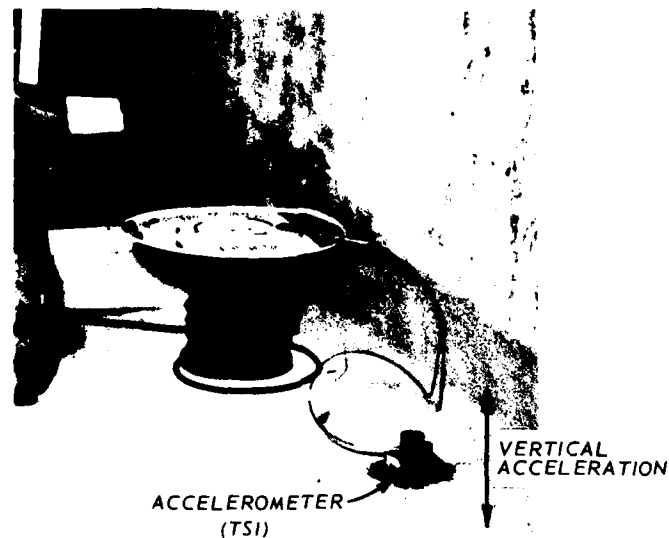


Figure 7. Accelerometer attached to gallery floor at el 247.0

Test Procedures

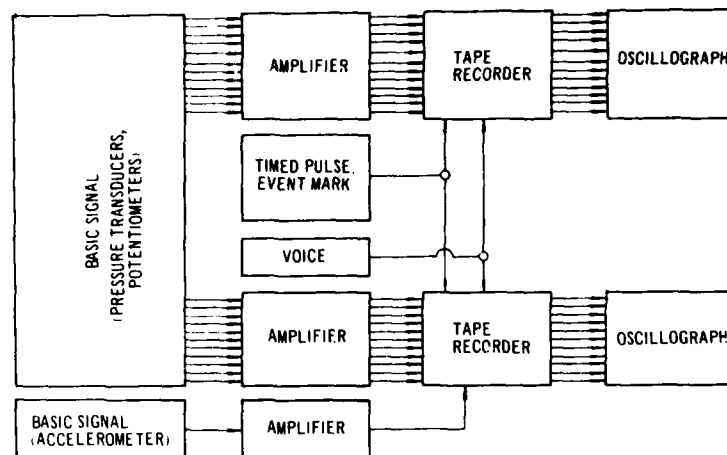
19. Thirty-three filling and twenty-one emptying tests were conducted during the period 12-16 July 1976 covering the range of hydraulic conditions given in Table 2.

Filling tests

20. Filling tests were conducted for lifts (difference in upper pool and initial lock water surface) ranging from 33.0 to 68.0 ft; valve times were varied from 53 to 259 sec. One- and two-valve operations were tested. Air vents remained closed for filling tests of lifts below 46.3 ft. The air vent valves were normally partly opened (four handle turns) for lifts greater than 46.3 ft; tests with air vent valves half open (13 turns) and fully open (26 turns) were also made.

Emptying tests

21. Emptying tests were conducted for heads ranging from 9.6 to 68.5 ft; valve times were varied from 53 to 135 sec. One- and two-valve operations were used.



a. Schematic of recording system



b. Recording system components

Figure 8. Recording equipment

PART III: DATA REDUCTION AND ANALYSIS

Data Reduction

Calibration factors

22. The typical format of the oscillograms is shown in Figure 9, an unscaled reproduction of test 48. The scale factors were determined by either electrical calibration steps or from a known change in static conditions. The latter method of scale determination was used where transducers were exposed to the hydrostatic pressure changes in the lock chamber (transducers TV1, TC1, TL1, TL2, TL3, TL4, TL5, LWS1, and DVW). For example, as shown in Figure 9, the lock water-surface elevations before and after test 48 (determined by staff gage readings in the chamber to be 213.5 and 253.6 ft, respectively) cause a chart displacement (designated "a" in Figure 9*) for TV1 of 0.97 in. Thus, the chart scaling factor for TV1 was:

$$\frac{253.6 - 213.5}{0.97} = 41.34 \frac{\text{ft of water}}{\text{in. of chart}}$$

Instantaneous piezometric pressure elevation during test 48 was then determined by measuring the trace displacement (y) in inches, multiplying by 41.34, and adding the result algebraically to 213.5. The accuracies for this method are less dependent on staff gage readings and the measuring system linearity than they are on scaling inaccuracies (i.e., a ± 0.02 -in. chart error causes a ± 0.8 -ft error in TV1).

23. All other pressures were scaled using the electrical calibration steps. The calibration step values are determined experimentally in the laboratory prior to field testing. For example, the calibration step value for UVW in test 48 was 66.0 ft of water. The corresponding

* For convenience, symbols are listed and defined in the Notation (Appendix B).

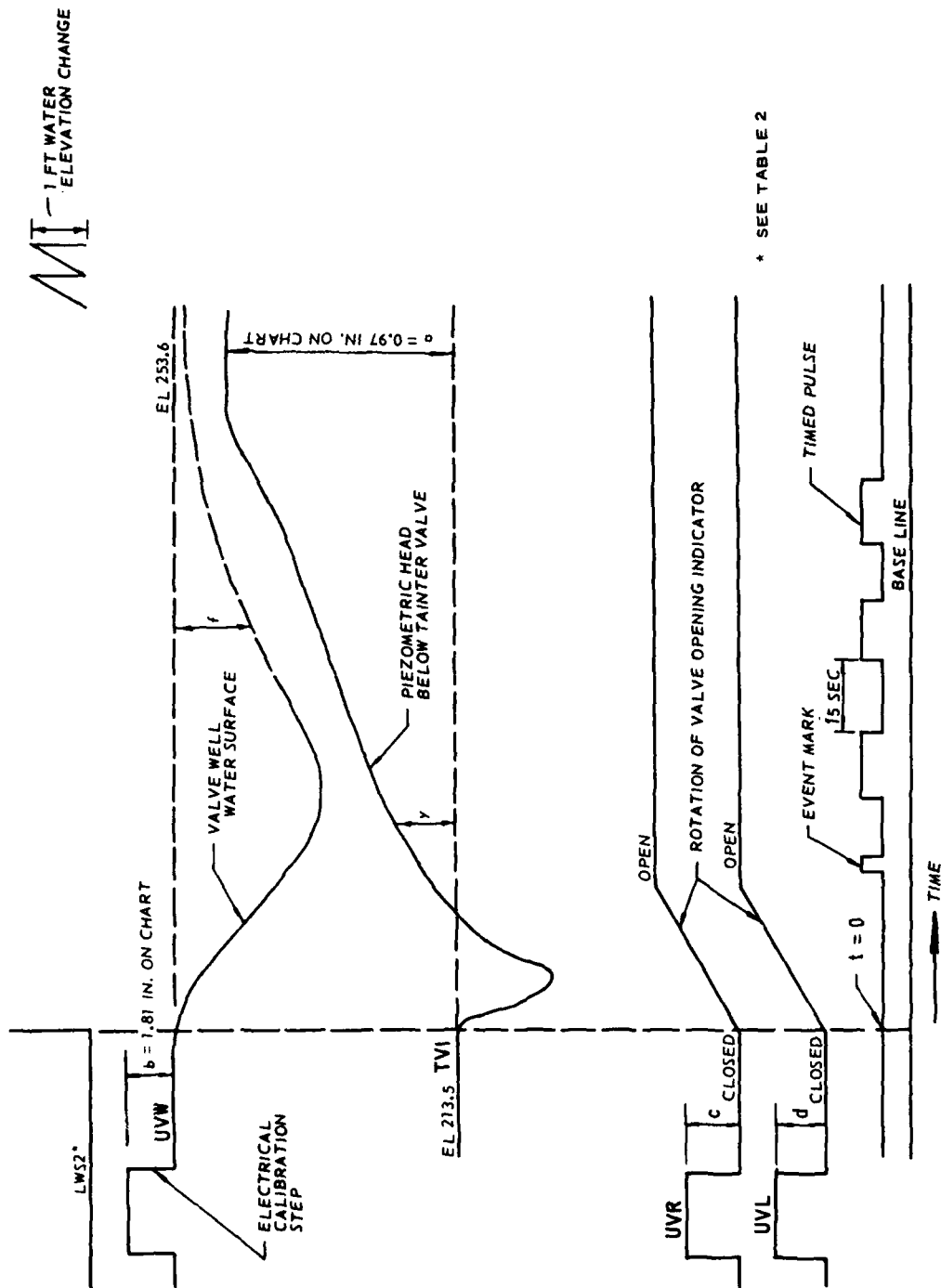


Figure 9. Typical format of oscillogram (test 48), not to scale

trace displacement (b from Figure 9) was 1.81 in. The scale factor was therefore

$$\frac{66.0}{1.81} = 36.46 \frac{\text{ft of water}}{\text{in. of chart}}$$

Therefore, any chart displacement f , in inches, corresponds to a $36.46f$ change in piezometric head elevation; i.e., $\Delta h = 36.46f$ for valve well water surface, test 48. Calibration steps are also shown for the upstream valve strut rotation (c and d in Figure 9). Prior to the test series the vertical gate opening was calibrated to this rotation.

Time correlation

24. As discussed in paragraph 18, time correlation between signals recorded simultaneously but on different tapes was assured by a common, continuous 15-sec timed pulse (Figure 9). An event mark, also shown in Figure 9, was superimposed on both pulse traces to indicate significant events such as start of test, start of valve openings, etc. This information was also recorded on the oscillograms.

Analytical Model of Lock Operation

25. Overview. A brief discussion of the analytical equations relevant to lock filling along with their importance in regard to model-prototype scaling is given in Appendix A. The computer program (math model) used for the numerical integration of the equations here is titled "H5320" and is described in an earlier report.* The procedure used to evaluate the overall loss coefficient, k_t , is denoted method 2 in Appendix A; the Bankhead operation times listed in Table 2 were used as input. The subdivision of losses for filling is as shown in Figure A2; for emptying the subdivisions and source of data are:

- a. Intake, k_1 : Lock chamber to transducer locations, TL4 and TL5.
- b. Upstream Conduit, k_2 : TL4 and TL5 to valve well transducer DVW.

* Martin T. Hebler and Frank M. Neilson. 1976 (Jun). "Lock Filling and Emptying Symmetrical Systems," Miscellaneous Paper H-76-13, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

- c. Downstream Conduit, k_3 : DVW to outlet manifold (no transducer).
- d. Outlet, k_4 : Outlet manifold to lower pool; this value is estimated from model data.

A summary of conditions and coefficients for the Bankhead prototype follows:

Condition		$k_1 + k_2$	k_3	k_4	k_t^*	$C_L^{**} \approx k_t^{-1/2}$
Operation	Valves					
Filling	1	0.40	0.52	0.21	1.23	0.90
Filling	2	0.40	0.45	0.70	1.65	0.78

Condition		k_1	k_2	$k_3 + k_4$	k_t^*	$C_L^{**} \approx k_t^{-1/2}$
Operation	Valves					
Emptying	1	0.42	0.90	0.93	2.35	0.65
Emptying	2	0.08	0.90	0.93	2.01	0.71

* For valve full open $k_v = 0.10$.

** See definitive Equation A2, Appendix A.

26. Interpretation. Once the above coefficients are established the analysis provides (for any combination of pool elevations, single or synchronous valve patterns, and filling or emptying operations) lock chamber levels, flow rates, and specific energy-grade-line elevations as well as other quantities derivable therefrom. Selected outputs from H5320 are presented concurrently with measured prototype values in Plates 2-9. Note that no modifications were added to the H5320 code; specifically (a) the valve loss coefficient and contraction coefficient are specific functions of valve opening ratio, b/B , and (b) the entire inertial effect is lumped into the length of culvert downstream from the operating valves. Since improving the precision of the program output was not a goal at Bankhead, these types of possible coding changes were not undertaken.

Data Analysis

Filling and emptying curves

27. Prototype lock water-surface data presented in Plates 2-5

were reduced from LWS2 and LWS3 data. The "sawtooth" line near the top of Figure 9 indicates the LWS2 recording. Each diagonal line represents 1.00 ft of change in the lock water surface. At the beginning of each test the lock water-surface elevation was recorded from one of the staff gages in the lock chamber. Therefore, the filling curves were determined by adding the total change registered by LWS2 to the initial reading; corrections using LWS3 data and/or overall static lift values were only occasionally warranted.

28. Plates 2 and 3 present piezometric pressure data obtained in the lock chamber during filling (LWS2). Plate 2 presents high-lift filling data for two-valve operations with 1-, 2-, and 4-min valve times. Plate 3 presents high-lift filling data for one-valve operation with 1-, 2-, and 4-min valve times. The tests presented in Plates 2 and 3 were conducted at lifts near the maximum for the lock; air was drawn through the air vents into the culvert system during these tests.

29. Plate 4 presents high-lift emptying data for a two-valve emptying operation at a 1-min opening time. Data are presented in Plate 5 for single-valve operation, 1-min valve-time, for each emptying valve test.

Valve well water-surface elevations

30. Upstream and downstream river-wall valve well water-surface elevations were determined from pressure transducers UVW and DVW, respectively. Scale factors for UVW were determined using electrical calibration steps whereas known elevation differences were used for scaling DVW. Upstream well measurements are shown in Plates 2 and 3 (filling tests); downstream well measurements are shown in Plates 4 and 5 (emptying tests).

Pressures downstream from filling valve

31. Transducer TV1, on the culvert wall about 13 ft downstream of the river-wall filling valve, measured pressure fluctuations for numerous filling test conditions. TV1 data were digitized during the valve operation period and mean, maximum, and minimum piezometric heads were calculated. These are presented for a variety of lifts for

two-valve operations in Plates 6 and 7 and for single-valve operations in Plates 8 and 9.

Math model comparisons

32. Calculated values, also presented in Plates 2-9--valve opening, valve well water-surface elevation, lock chamber water-surface elevation, and piezometric pressure on the culvert roof downstream of the filling valve--generally are in good agreement with measured values. Low pressures at TV1 during valve opening are of particular concern from the point of view of air venting--some disparities are evident between calculated and measured values. These differences are attributed, first, to coding limitations (with regard to inertial effect; see paragraph 26) which result in a higher calculated than measured minimum pressure (as in Test 31, Plate 2) and, second, to cavitation below the prototype valve (tending to limit the actual pressure drop) which results in a lower calculated than measured minimum pressure (as in Tests 39 and 42, Plate 2).

Floor culvert pressures

33. The piezometric heads at the five locations (TL1-TL5) in the floor culvert system during filling are shown in Figure 10. Prototype tests 33 (single valve) and 36 (two valves) are presented along with two comparable physical model tests. Physical model data were taken at the invert of the culvert at el 159.5 and prototype data were taken at the roof at el 169.0; all data are for 90 sec from start of test. Manifold loss coefficients (see Appendix A) using data from Figure 10 for tests 33 and 36 are presented in Figure 11. The difference in piezometric head between TL4 and TL5 (Figure 10) as well as the corresponding difference in loss coefficient (Figure 11) indicates a small (undesired) imbalance in flow conditions between the two manifolds.

Tuning-fork roof pressure

34. The pressure on the inside roof (el 169.0) of the 22-ft-wide span of the tuning fork-shaped bifurcation section of the floor culvert system (TL1) is shown in Plate 10. These data are for emptying tests (two-valve operation, 1-min valve time) with lifts ranging from 19.5 to 67.7 ft. Since the span of the culvert roof is large at this location, the maximum differential pressure (above roof minus inside culvert) is

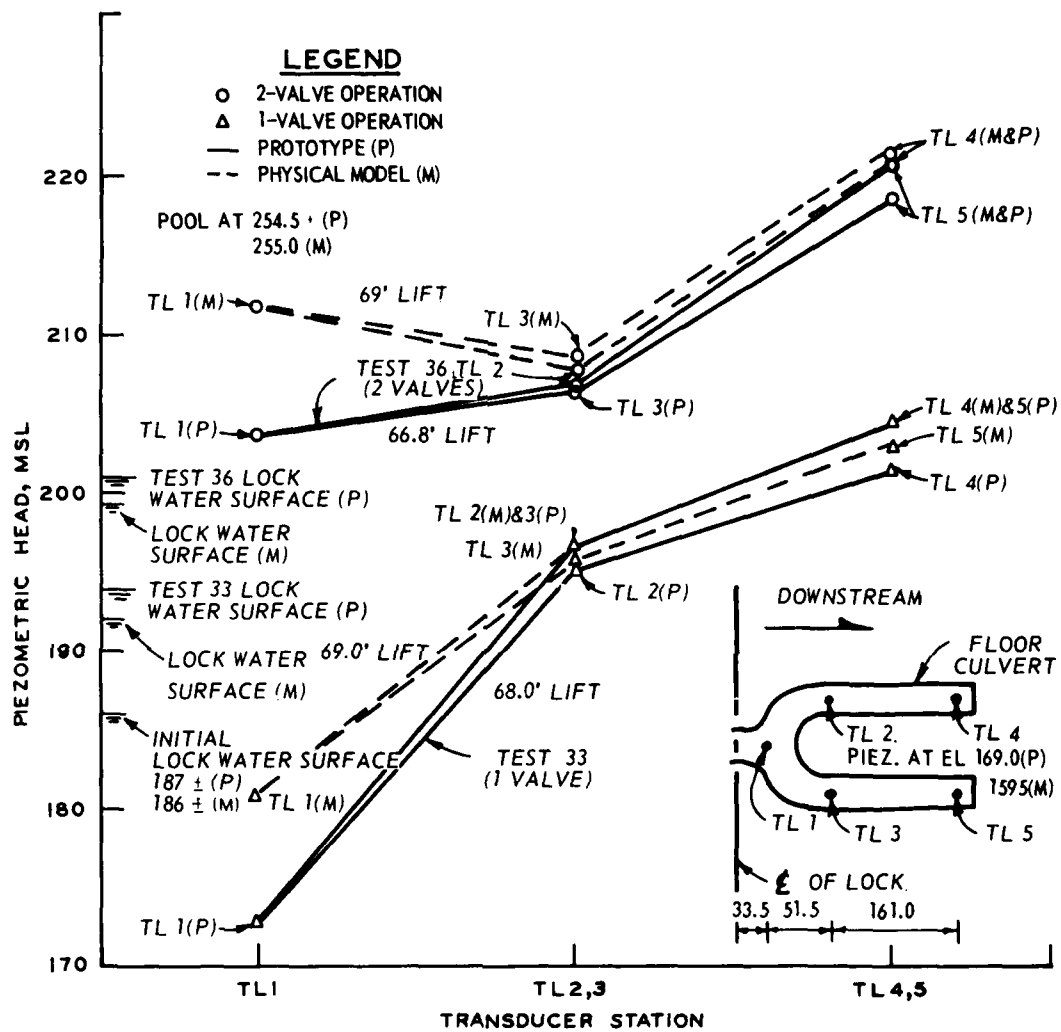


Figure 10. Piezometric head in the filling manifold
at $t = 90$ sec ($t_v = 56$ sec (P), 60 sec (M))

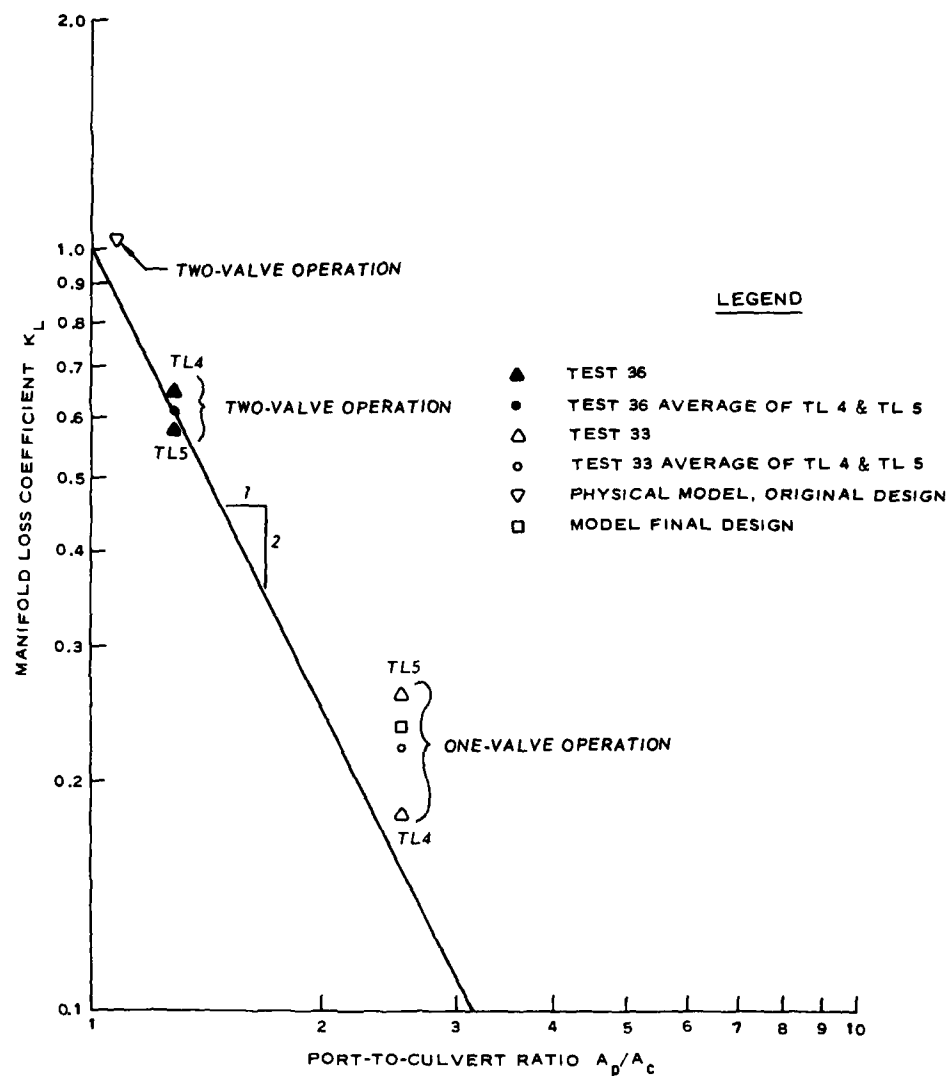


Figure 11. Port-culvert ratio versus manifold loss coefficient

of concern, structurally. Selected specific values (two-valve operation, prototype and model, high initial head) are as follows:

Source	Lock Water Surface ft msl	TL1 Piezometric Head			Differential	
		Average ft msl	Instant. ft msl	Low ft msl	Avg ft	Max ft
Prototype test 103	249.5	215.0	212.0		34.5	37.5
Model*	248.0	212.0	210.0		36.0	38.0

* Oswalt, Ables, and Murphy, op cit.

Pressure fluctuation

35. Plates 10-17 show analog emptying data taken at transducers TL1, TV1, TB1, and TC1. Plates 10-13 are for 1-min, two-valve operations and Plates 14-17 are for 1-min river-wall valve operations. Examination reveals that pressure fluctuations, which were apparently generated near TC1, affect pressures throughout the system. During these emptying operations, noises presumed to be from cavitation were audible. Measured pressure fluctuations at TC1 as large as 113 ft of water were recorded during test 14 (Plate 13) with instantaneous low pressures reaching near a negative 25 ft of water. Unfortunately, transducer TC1 malfunctioned during test 16 (Plate 17) and was not operable during the remainder of the tests; therefore, lifts of 48.9 ft and 49.2 ft for one- and two-valve operations, respectively, are the greatest for which TC1 data are available. However, TL1, TV1, and TB1 data extend to a lift of 67.7 ft (two-valve operation, Plates 10-12) and to a lift of 65.8 ft (river-wall valve operation, Plates 14-16). Since the trend of all these data indicates increasing magnitude of pressure fluctuations with lift throughout the emptying system, the pressure fluctuations at TC1 probably also become more severe.

36. Analog data at TV1 (immediately downstream of the filling valve) for a series of filling operations are presented in Plates 18-21. Plates 19 and 21 present 25 sec of analog data played back from the magnetic tape at a chart speed five times the rate presented in Plates 18 and 20, respectively. These data were taken between 40 and 65 sec after the valve began to open. This represents a period when pressure

fluctuations were the greatest and instantaneous pressures reached minimums. No air was drawn in any of these tests with the possible exception of test 47 in which the data were incomplete. It should be noted that in tests 23, 25, 27, 29, and 46 no air was drawn even though the air vents were open.

Valve hoist loads

37. Hydraulic hoist cylinder differential pressures required to raise the tainter valve were determined from the analyses of tests 33 and 40. The calculated differential pressures and forces are plotted in Figure 12 with respect to valve opening. Test 33 was a 1-min, single-valve operation and test 40 was a 2-min, one-valve operation. The pressures in both cases follow the same trend with the 1-min valve

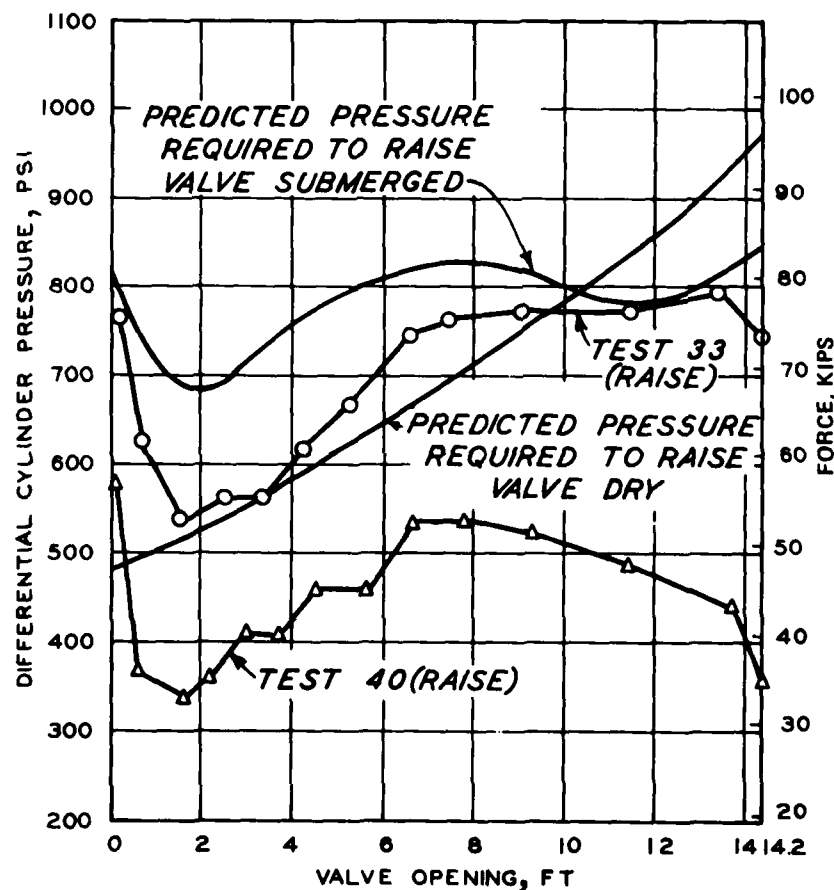


Figure 12. Cylinder pressure curve

pressures being 200 to 300 psi greater. Figure 12 also shows predicted load curves for submerged and dry valve operations as presented in the new John Hollis Bankhead construction drawings.

Piezometric head
across the filling valve

38. The piezometric pressure drop across the filling valve was computed from the difference in the upstream valve well (UVW) and culvert transducer below the valve (TV1) pressures and is presented in Figure 13 for tests 21 and 40. Test 21 was for the river-wall valve only with a valve time of 1 min and a lift of 43.9 ft. Test 40 was for the river-wall valve only with a 2-min valve time at a lift of 67.0 ft. The prototype data are compared in Figure 13 with H5320 (math model) calculated values for the same tests.

Contraction coefficients

39. Contraction coefficients were computed using prototype data from tests 21 and 40 which included valve well water-surface elevations (UVW) and the piezometric head downstream of the valve (TV1), as stated in paragraph 38, and discharges from the math model data. The contraction coefficient was computed from this equation

$$C_c = \frac{Q}{bw \left[2g \left(\frac{V_c^2}{2g} + p_1 - p_2 \right) \right]^{1/2}}$$

where

- C_c = contraction coefficient
- Q = discharge (math model values)
- b = vertical valve opening
- w = width of culvert downstream of valve
- g = acceleration due to gravity
- V_c = mean culvert velocity
- p_1 = piezometric head elevation at valve well (UVW)
- p_2 = piezometric head elevation downstream of the valve (TV1)

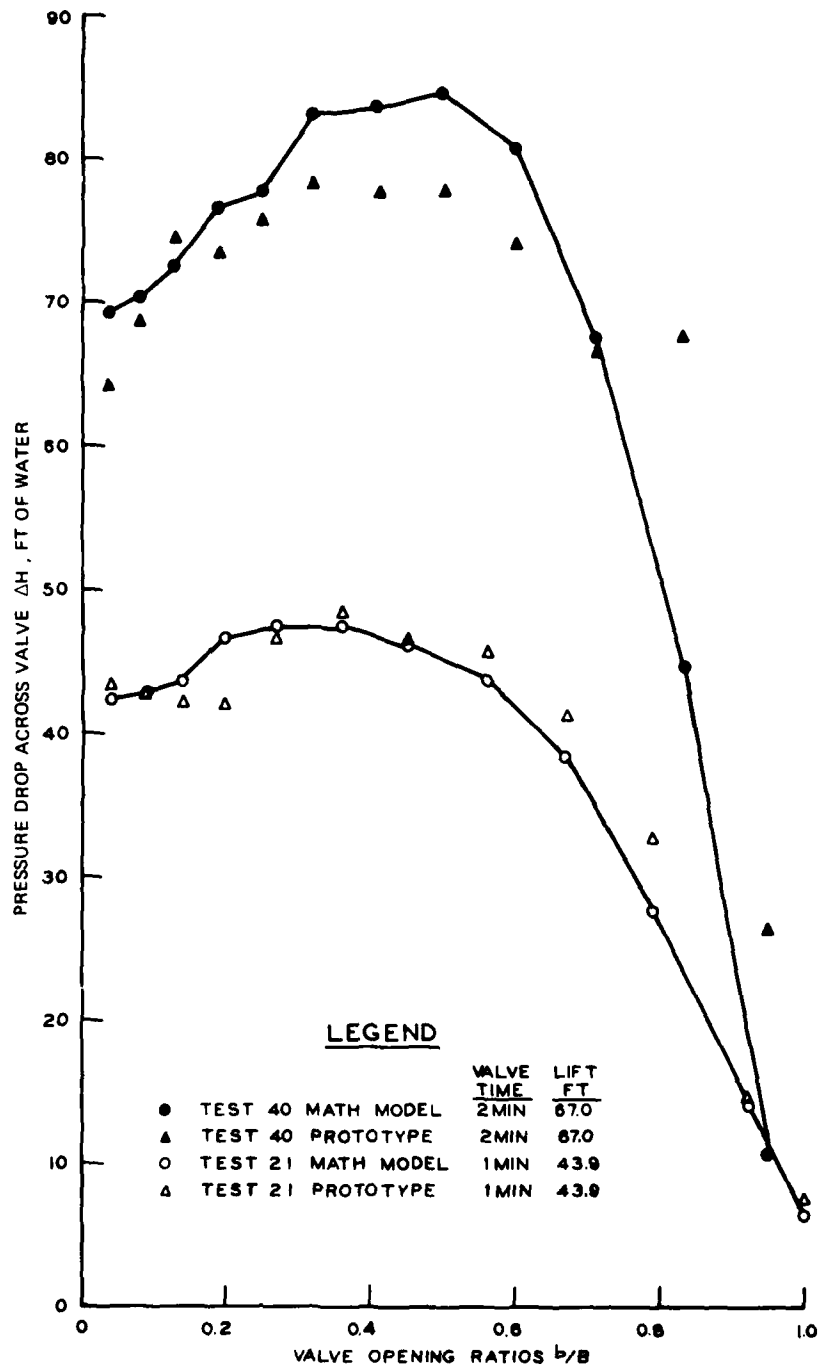


Figure 13. Comparison of lock program and prototype pressure drop between upstream river-wall valve well and the culvert transducer below valve

The resulting values are plotted in Figure 14; the function used in the math model to compute C_c is also shown along with the values for C_c obtained using the Von Mises equation.* The symbol β represents the angle of the gate lip with the horizontal. The Bankhead filling valve is shown in Plate 22.

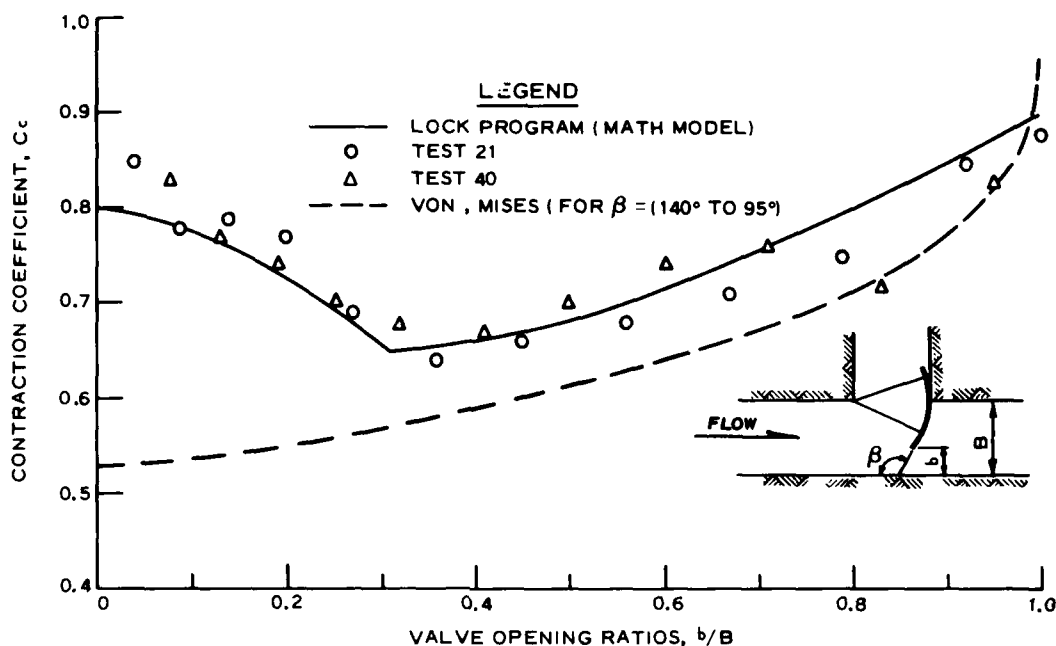


Figure 14. Reverse tainter valve contraction coefficient
Air demand

40. With vents open, air was drawn into the culvert for lifts greater than 54 ft during 1-min, single-valve tests and for lifts greater than 54.7 ft for 1-min, two-valve operations. As expected, pressure fluctuations at TV1 during air flow extended below the roof of the culvert; and conversely, during the lower lifts at which practically no air flow occurred, the pressure head generally exceeded the elevation of the roof of the culvert. Test 29 (Plate 8) is an example of a test in which air flow occurred and the instantaneous pressures at TV1

* Maurice James, "Analytical Determination of Contraction Coefficients Using Complex Potential Theory," memorandum for file, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

approached the vapor pressure of water (-34 ft H_2O or el 135.9). Tests conducted near maximum lift revealed air being drawn between b/B of 0.24 and 0.85. Figure 15 shows air demand curves for three similar

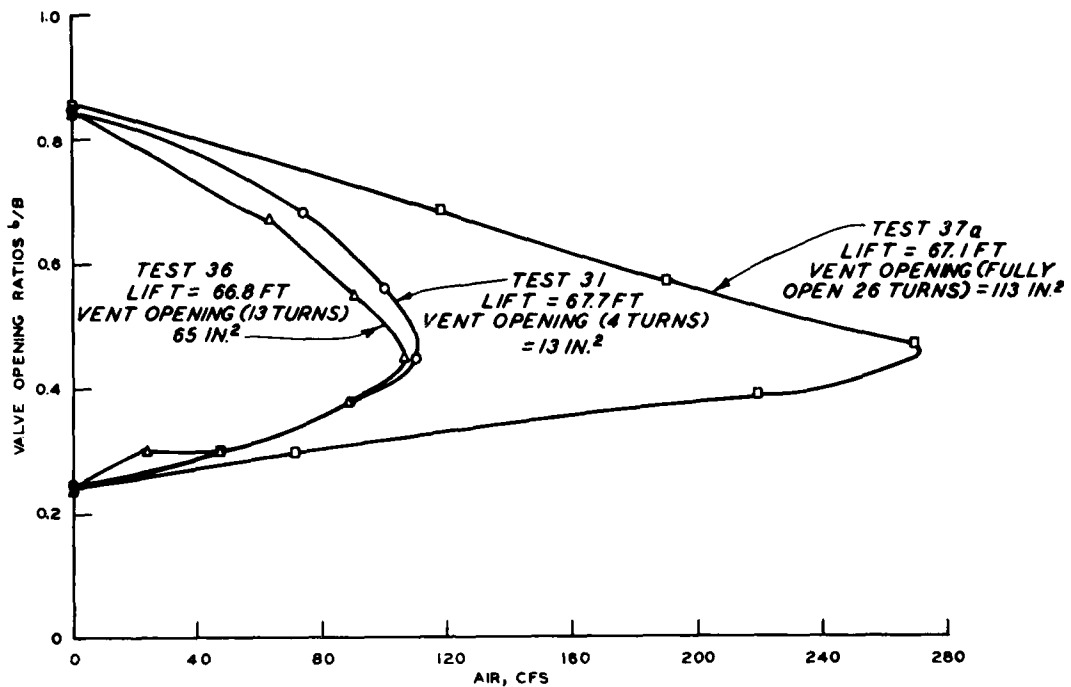


Figure 15. Air demand curve for river-wall filling valve

lifts with varied air vent openings, all of which drew air in the stated b/B range. These tests indicate that air vent openings of 4 and 13 turns varied only slightly in volume of air drawn. However, when the valve is fully open (26 turns), the air flow is substantially increased.

Structure vibration

41. The amplitude of the vibrations measured in the river-wall gallery (TS1) was considered insignificant structurally and is not presented here. Inspection of the test data showed that the dominant vibration frequencies correlated reasonably well with the pressure fluctuations at station TC1 (directly below station TS1).

Upstream surge

42. The water-surface elevation in the upstream channel was continuously monitored using a water level recorder on the river guide

wall. The maximum surge, 1.8 ft, occurred immediately following the beginning of test 20, two-valve filling. The corresponding period of surging was 11.5 min.

Valve opening pattern

43. The valve opening pattern is shown in Figure 16. The valve

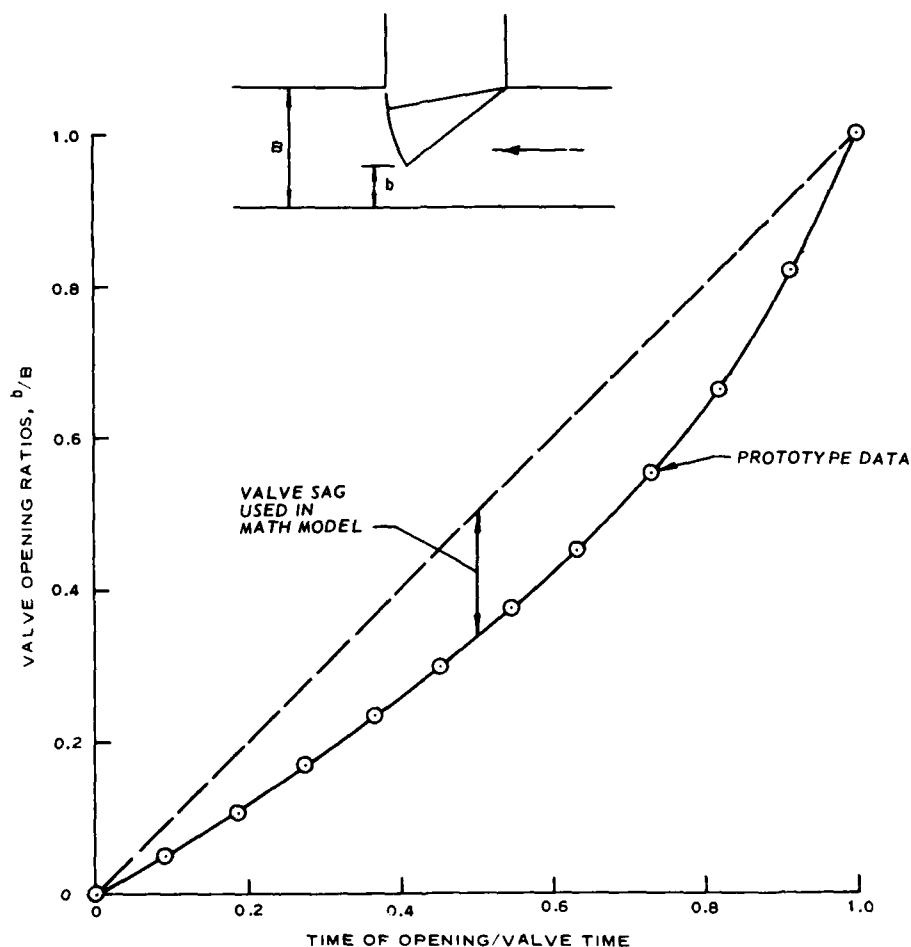


Figure 16. Valve opening pattern

sag coefficient determined from field measurements was used as input to the math model as described in the reference of paragraph 25.

Physical model data

44. Plate 23 compares valve opening test data of the physical model and the prototype-adjusted math model. The greatest difference

exists between data taken at TV1 in the prototype at sta 2+09.8A, el 169.9, and in the physical model at sta 2+10.0A, el 169.0. Slight differences exist in the lock water-surface data, which could be a result of the greater efficiency of the prototype. A comparison of prototype and physical model loss coefficients is presented in Appendix A.

PART IV: CONCLUSIONS

45. The following determinations and conclusions result from analyses of the reduced data of the Bankhead Lock prototype tests.

Culvert Pressures

46. Average pressures less than atmospheric were experienced at pressure transducer TV1 for conditions discussed in paragraph 40. With moderately high-lift conditions (test 29 for example), average piezometric pressures were higher than the roof elevation of the culvert while minimum instantaneous pressures were near the vapor pressure of water. This indicated that the positive average pressures from submergence of the valve prevented air being drawn through the vents, which in turn permitted fluctuations to extremely low pressures.

47. Pressures throughout the culvert system were substantially affected by phenomena occurring near TC1 during emptying operations. Banging noises and shock-type pressures in this general area were detected at other measurement points. The crossover section of the culvert system should be inspected periodically for possible cavitation damage. Pressures in the chamber culverts as presented in Figure 10 indicated a slight imbalance of flow between the two arms of the tuning fork bifurcation; flows appeared only slightly more balanced in two-valve than in one-valve operation.

Air Demand

48. Observed volumes of air intake at high lifts indicate that increasing vent openings from 4 to 13 turns has very little effect on the air flow rate (Figure 15). However, as the vents approach fully open, the volume of air drawn substantially increases.

Model-Prototype Comparison

49. Overall model-prototype comparisons and recommendations are

included in Appendix A. As expected, the physical model is less efficient than the prototype and has lower peak velocities and flow rates. It is suggested (and is the current procedure) that an analytical description of the lock operation be used to evaluate specific items (extremely low pressures in the culvert system, for example) that are highly dependent on flow velocities.

Table 1
Prototype Instrumentation

Prototype Code	Transducer			Location		Measurement	Computed Results	Cable Length ft
	Model Code	Type	Range	Station	El Position			
UVW	--	Press CEC 4-312	50 psia	1+71.0A	200.0	US valve well (RW)	Pressure	Well water-sur el 285
DVW	--		50 psia	5+05.0A	184.0	DS valve well (RW)		Well water-sur el 650
AV1	--		+1.0 psid	1+90.0A	258.0	Air vent (RW)		Air demand 225
AV2	--		+1.0 psid	1+90.0A	258.0	Air vent (RW)		Air demand 225
LWS1	Press		50 psia	2+45.0A	182.0	Lock wall (RW)		Lock water-sur el 460
LWS2	Cam	Potentiometer	360°	2+47.0A	262.0	Top of lock (RW)	Vert change	Lock water-sur el 425
LWS3	Press	Press CEC 4-312	25 psia	2+47.0A	Varies	Mooring bitt (RW)	Pressure	Lock water-sur el 525
UVL	Cam	Potentiometer	90°	1+85.3A	261.0	Lever arm (LW)	Valve opening	Valve opening 760
UVR				1+85.3A		Lever arm (RW)		210
DVL				5+19.3A		Lever arm (LW)		125
DVR				5+19.3A		Lever arm (RW)		75
GUL				0+00.0A	262.0	Gudgeon pin	Angle change	Miter gate open 590
GUR				0+00.0A				75
GDL				6+70.0A				1290
GDR				6+70.0A				740
VPF	--	Press CEC 4-313	2000 psia	1+93.5A	260.0	Valve cylin (RW)	Pressure	Vert valve load 220
VPB	--	Press CEC 4-313	2000 psia	2+07.5A	260.0	Valve cylin (RW)		Vert valve load 235
TL1	6-E	Press CEC 4-312	50 psia	3+65.5A	169.0	Long fill culv		Head, head diff 580
TL2	7-E			4+17.0A				670
TL3	9-E			4+17.0A				670
TL4	8-E			5+78.3A				850
TL5	10-E			5+78.3A				850
TV1	7-B		100 psia	2+09.8A	169.9	Fill culv (RW)		Press fluctuations 615
TC1	--		100 psia	3+50.7A	169.4	Empty culv (RW)		Press fluctuations 535
USS	--	Microswitch	--	0+19.5B	268.0	US miter gates	Change	Closed+opening 165
DSS	--	Microswitch	--	6+50.5A	268.0	DS miter gates	Change	Closed+opening 835
TB1	--	Press CEC 4-312	50 psia	2+20.0A	189.0	Bulkhead seal	Pressure	Press fluctuations 340
TS1	--	Accelerometer	1-20 g	3+50.7A	247.0	River-wall gallery	Acceleration	Accelerations 470

Note: RW = River wall; LW = Land wall.

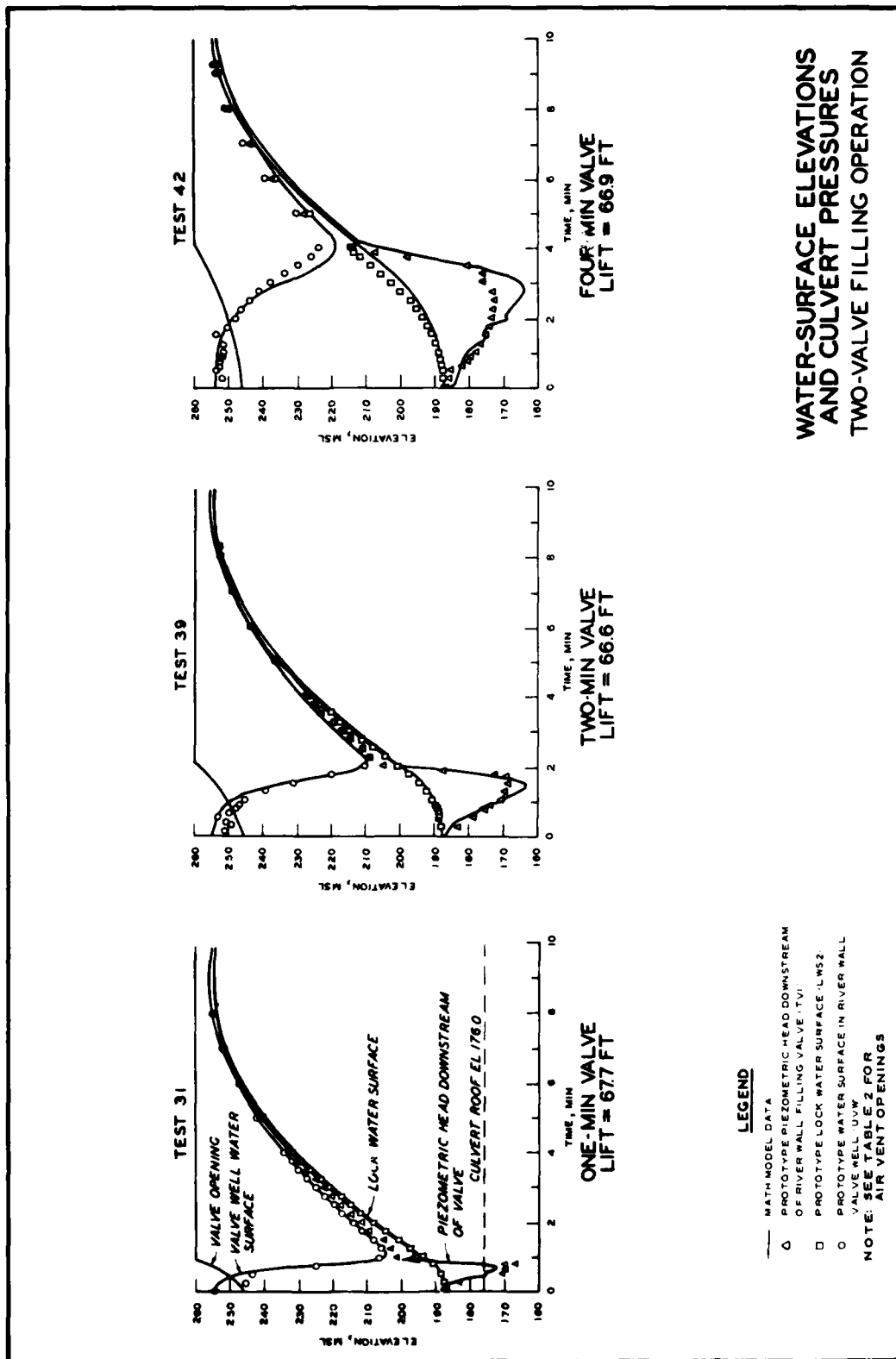
Table 2
Test Conditions and Selected Data

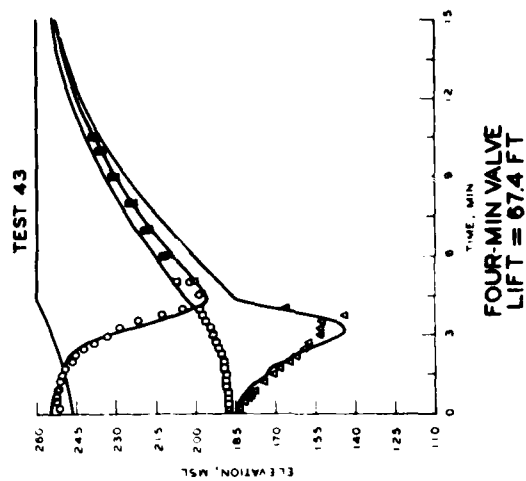
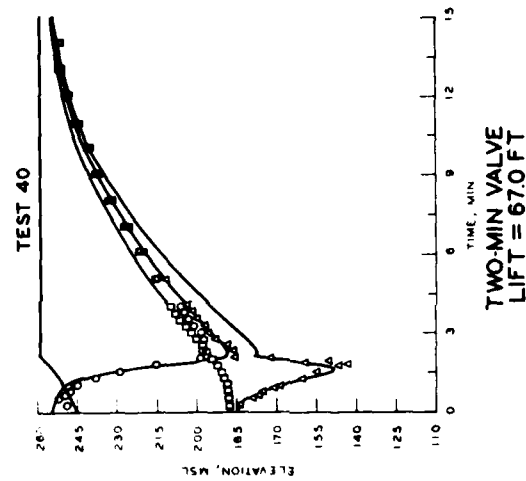
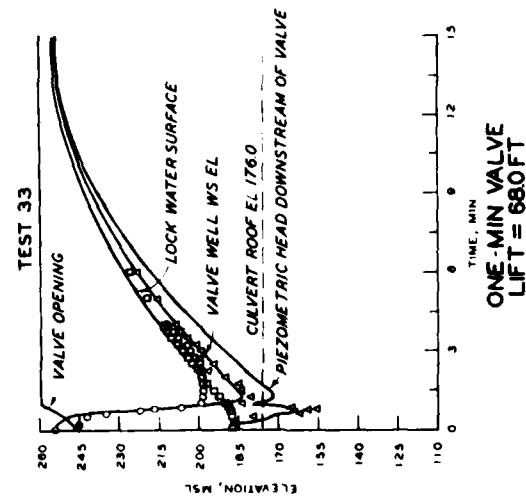
Test No.	Order No.	Empt- ying or Fill- ing	Initial Head Differ- ential ft.	Initial Elevation, mal			Valve Time, sec				No. of Valves Opened	Air Vents			Maximum Pressure Fluctuation at TVI						Over- travel ft.	Test Date July 1976					
				Lock MS	Pool	Tailwater	Filling		Emptying			Open or Closed	Turns Open	Air Drawn	Time, sec		Valve Opening, ft		Maximum Fluc- tuation	Lowest Pressure			Maximum Fluc- tuation	Lowest Pressure	Filling	Emptying	
							Begin	End	Begin	End					Begin	End	Begin	End								Begin	End
1	1	E	9.9	195.9	--	186.0	--	--	55.5	58.0	2	--	--	--	--	--	--	--	--	--	--	207	1.1	12	10		
2	2	E	9.6	196.0	--	186.4	--	--	55.0	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	12	11	
3	3	E	13.5	205.8	--	186.3	--	--	55.0	60.0	2	--	--	--	--	--	--	--	--	--	--	--	--	--	12	11	
4	4	E	19.2	205.8	--	186.6	--	--	56.0	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	12	11	
5	5	E	30.1	216.4	--	186.3	--	--	53.0	58.0	2	--	--	--	--	--	--	--	--	--	--	361	1.1	12	11		
6	6	E	24.0	215.5	--	186.4	--	--	53.0	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	12	11	
7	7	E	39.2	225.9	--	186.7	--	--	54.0	58.0	1	--	--	--	--	--	--	--	--	--	--	--	--	--	12	11	
8	8	E	39.1	225.8	--	186.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	747	0.4	12	11		
101	9	F	66.6	188.0	254.6	--	211.6	191.0	Not full open	--	--	--	--	Yes	--	--	--	--	--	--	--	--	--	--	12	10	
9	10	F	33.1	221.4	254.5	--	55.5	53.0	--	--	1	--	--	--	41	46	43	--	3.4	--	--	3.4	--	1.3	13	11	
10	11	E	49.2	236.0	--	186.8	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	461	1.2	--	13	11	
102	12	F	68.0	186.6	254.6	--	17.4	17.5	Not full open	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	13	11	
11	13	F	33.0	221.4	254.4	--	55.0	--	--	--	1	--	--	--	40	41	43	--	--	--	--	--	--	--	13	11	
12	14	E	66.9	253.3	--	186.4	28.1	--	Not full open	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	13	11	
13	15	F	38.9	215.6	254.5	--	55.0	51.5	--	--	1	--	--	--	47	49	40	--	3.7	7.7	351	--	1.1	13	11		
14	16	E	49.2	236.0	--	186.8	--	--	53.5	57.0	1	--	--	--	--	--	--	--	--	--	--	419	--	--	13	11	
15	17	F	49.1	215.5	254.6	--	55.4	--	--	--	1	--	--	--	43	54	47	--	9.1	9.1	623	--	--	13	11		
16	18	E	48.9	236.0	--	187.1	--	--	54.0	--	1	--	--	--	--	--	--	--	--	--	--	555	--	--	13	11	
17	19	F	43.4	211.1	254.5	--	54.0	57.0	--	--	1	--	--	--	47	48	45	--	4.9	18.0	373	--	--	13	11		
18	20	F	48.6	206.3	254.6	--	131.5	104.7	--	--	1	--	--	No	87	119	112	--	14.9	14.9	431	--	1.3	14	11		
19	21	E	46.7	233.7	--	186.8	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	591	1.2	14	11		
20	22	F	58.0	191.1	254.5	--	149.0	100.0	--	--	1	--	--	No	89	127	114	--	10.9	9.2	473	--	1.4	14	11		
21	23	F	44.9	210.8	254.7	--	54.0	--	--	--	1	--	--	--	39	53	49	--	10.6	10.6	666	--	--	14	16		
22	24	E	59.4	246.0	--	186.4	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	482	--	--	14	16	
23	25	F	44.7	210.3	254.7	--	54.0	57.0	--	--	1	--	--	No	40	50	44	--	9.4	9.4	390	--	1.3	15	09		
24	26	E	59.7	246.5	--	186.7	--	--	54.0	--	1	--	--	--	--	--	--	--	--	--	--	965	--	--	15	10	
25	27	F	47.3	206.6	254.4	--	54.0	--	--	--	1	--	--	No	38	50	42	--	7.3	7.3	683	--	--	15	11		
26	28	E	65.5	253.3	--	187.0	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	--	--	--	15	12	
27	29	F	44.7	199.9	254.6	--	54.0	57.0	--	--	1	--	--	No	39	49	46	--	9.8	11.3	411	--	1.4	15	11		
28	30	E	47.8	254.0	--	186.4	--	--	54.0	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	15	13	
29	31	F	74.3	200.6	254.7	--	54.0	--	--	--	1	--	--	No	39	50	41	--	8.5	9.7	--	--	--	15	11		
30	32	E	65.8	252.9	--	187.1	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	--	--	--	15	11	
31	33	F	47.1	196.9	254.1	--	54.0	--	--	--	1	--	--	Yes	30	49	43	--	3.8	9.6	461	--	--	15	11		
32	34	E	65.4	252.3	--	186.4	--	--	54.0	57.0	1	--	--	--	--	--	--	--	--	--	--	1036	--	--	15	16	
33	35	F	68.0	196.4	254.4	--	54.0	--	--	--	1	--	--	Yes	39	53	47	--	10.6	11.8	820	--	2.7	15	16		
34	36	F	43.0	191.0	254.1	--	54.0	57.0	--	--	1	--	--	Yes	36	51	50	--	11.6	11.6	--	--	--	15	17		
35	37	F	46.8	187.1	253.8	--	--	54.0	--	--	1	--	--	Yes	--	--	--	--	--	--	--	827	--	--	16	11	
36	38	F	46.8	187.8	254.1	--	54.0	57.0	--	--	2	--	--	Yes	37	50	46	--	10.2	10.2	462	--	1.3	16	11		
37	39	F	67.0	197.5	254.6	--	55.0	53.0	--	--	2	--	--	Yes	40	50	46	--	10.6	11.5	--	--	--	16	09		
103	40	E	67.7	254.1	--	187.2	--	--	62.0	57.6	2	--	--	--	--	--	--	--	--	--	--	559	--	--	16	10	
37A	41	F	67.1	187.1	254.2	--	55.5	53.0	--	--	2	--	--	Yes	41	54	48	--	10.9	11.1	--	--	--	16	10		
104	42	E	65.5	254.5	--	187.1	--	--	54.0	57.0	2	--	--	--	--	--	--	--	--	--	--	539	--	--	16	11	
38	43	F	67.0	187.4	254.6	--	55.3	55.3	--	--	2	--	--	Yes	38	52	50	--	11.8	11.0	--	--	--	16	11		
39	44	F	66.6	187.9	254.5	--	173.0	101.0	--	--	2	--	--	Yes	74	108	103	--	6.0	7.1	188	--	1.4	16	11		
40	45	F	67.0	187.9	254.9	--	124.0	--	--	--	1	--	--	Yes	56	62	86	--	4.3	6.1	834	--	--	16	11		
41	46	F	67.0	187.9	254.9	--	--	101.0	--	--	1	--	--	--	48	94	60	--	--	--	--	824	--	--	16	11	
42	47	F	66.9	187.3	254.2	--	251.0	170.0	--	--	2	--	--	Yes	161	232	190	--	8.3	9.6	552	--	--	16	11		
43	48	F	67.4	187.4	254.1	--	259.0	--	--	--	1	--	--	Yes	216	239	231	--	11.0	11.0	--	--	--	16	11		
44	49	F	43.4	191.0	254.3	--	56.0	--	--	--	1	--	--	Yes	40	49	53	--	9.2	9.2	--	--	--	16	11		
45	50	F	46.3	207.8	254.1	--	56.0	73.0	--	--	2	--	--	--	45	55	53	--	12.8	12.8	382	--	--	16	11		
46	51	F	57.4	196.3	253.9	--	--	--	--	--	--	--	--	No	41	50	46	--	10.0	10.0	--	--	--	16	11		
47	52	F	57.4	196.4	254.2	--	N/A	--	--	--	--	--	--	N/A	40	50	41	--	--	--	--	--	--	16	11		
48	53	F	57.4	213.5	254.3	--	56.2	--	--	--	1	--	--	--	42	52	46	--	10.2	10.2	--	--	--	16	11		
49	54	F	44.4	187.9	254.2	--	109.5	119.0	--	--	2	--	--	Yes	86	103	98	--	9.1	9.1	509	--	1.5	16	11		

Table 2

Conditions and Selected Data

Maximum Pressure Fluctuation at TVI										Test Date July 1976	Zero Time CST	Wind Speed mph	Wind Azimuth deg	Temperature, °F	
Air Draw	Time, sec		Maximum Fluc- tuation	Lowest Pressure	Maximum Fluc- tuation	Lowest Pressure	Lock Time, sec		Over- travel ft					Air	Water
	Begin	End					Filling	Emptying							
--	--	--	--	--	--	--	--	207	1.1	12	104338	3.7	225	90	85
--	--	--	--	--	--	--	--	--	--	12	111415	3.7	270	88	
--	--	--	--	--	--	--	--	--	--	12	115055	3.7	225	91	
--	--	--	--	--	--	--	--	--	--	12	130950	5.0	300	92	
--	--	--	--	--	--	--	--	360	1.1	12	143456	4.76	255	94	
--	--	--	--	--	--	--	--	--	--	12	152036	4.76	255	93	
--	--	--	--	--	--	--	--	--	--	12	172950	6.67	255	91	
--	--	--	--	--	--	--	--	747	0.4	12	182036	3.7	250	90	
Yes	--	--	--	--	--	--	--	--	--	12	103250	3.7	275	38	
--	41	46	43	43	9.3	9.3	324	--	1.3	13	111655	3.7	270	92	84
--	--	--	--	--	--	--	--	405	0.9	13	115030	3.7	285	92	
--	--	--	--	--	--	--	--	--	--	13	131724	6.89	255	96	
--	40	51	43	43	9.2	9.2	--	--	--	13	134359	6.89	240	97	
--	--	--	--	--	--	--	--	--	--	13	141823	5.00	270	99	
--	37	49	40	40	8.5	8.5	355	--	1.1	13	144249	5.00	255	98	
--	--	--	--	--	--	--	--	459	--	13	151527	5.00	255	99	
--	43	54	47	47	9.1	9.1	623	--	--	13	161437	5.00	240	97	
--	--	--	--	--	--	--	--	855	--	13	170011	4.26	45	87	
--	37	48	45	46	9.9	10.0	373	--	1.1	13	181625	4.26	260	82	86
No	47	119	112	112	14.9	14.9	431	--	1.3	14	134256	3.57	180	97	86
--	--	--	--	--	--	--	--	591	1.2	14	140936	3.57	195	99	85
No	36	127	114	105	10.9	9.2	473	--	1.4	14	145059	3.57	285	100	
--	39	53	49	49	10.6	10.6	666	--	--	14	161831	3.57	45	95	
--	--	--	--	--	--	--	--	482	--	14	164544	4.76	45	97	
No	42	50	44	44	9.4	9.4	390	--	1.3	15	094019	3.45	235	73	
--	--	--	--	--	--	--	--	965	--	15	100954	3.45	205	77	84
No	38	52	42	42	7.3	7.3	683	--	--	15	114624	3.45	330	90	
--	--	--	--	--	--	--	--	--	--	15	125428	4.08	225	90	
No	37	49	46	49	9.8	11.3	411	--	1.4	15	131136	4.08	358	91	
--	--	--	--	--	--	--	--	--	--	15	133258	4.08	305	92	
No	39	50	41	47	8.5	9.7	--	--	--	15	135339	4.08	195	92	
--	--	--	--	--	--	--	--	--	--	15	140950	4.08	240	93	
Yes	36	49	43	46	8.8	9.6	465	--	--	15	152000	5.50	240	94	
--	--	--	--	--	--	--	1036	--	--	15	167850	5.50	225	94	
Yes	39	53	47	50	10.6	11.8	820	--	2.7	15	164860	3.51	241	92	
Yes	36	51	50	50	11.6	11.6	--	--	--	15	174149	4.01	45	96	
Yes	--	--	--	--	--	--	827	--	--	16	182036	3.51	180	96	
Yes	37	50	46	46	10.2	10.2	462	--	1.3	16	--	--	--	--	
Yes	40	50	46	48	10.7	11.5	--	--	--	16	094540	4.71	225	97	
--	--	--	--	--	--	--	--	550	--	16	100417	4.71	225	97	
Yes	41	54	48	52	10.9	11.7	--	--	--	16	105540	4.71	225	97	
--	--	--	--	--	--	--	--	530	--	16	115248	4.71	225	97	
Yes	38	52	50	52	11.8	11.8	--	--	--	16	125655	4.71	225	97	
Yes	74	108	103	101	6.0	6.0	488	--	1.4	16	130860	5.50	240	97	
Yes	36	42	36	39	4.3	6.1	834	--	--	16	136100	5.50	240	97	
--	48	44	40	60	--	--	824	--	--	16	141743	4.71	225	97	
Yes	161	240	190	175	8.3	9.6	552	--	--	16	150407	4.71	225	97	
Yes	216	289	241	241	11.0	11.0	--	--	--	16	154041	4.71	225	97	
Yes	40	54	53	53	9.2	9.2	--	--	--	16	162902	4.71	225	97	
--	45	55	53	53	10.8	10.8	382	--	--	16	170029	4.71	225	97	
No	41	52	47	47	10.3	10.7	--	--	--	16	173719	4.71	225	97	
S/A	40	52	41	41	--	--	--	--	--	16	180357	4.71	225	97	
--	40	52	47	48	10.7	10.7	--	--	--	16	184752	4.71	225	97	
Yes	39	113	95	79	9.1	9.1	500	--	1.5	16	--	--	--	--	





LEGEND

MATH-MODEL DATA

PROTOTYPE PIEZOMETRIC HEAD DOWNSTREAM OF FULL VALVE LIFT

PROTOTYPE LOCK WATER SURFACE

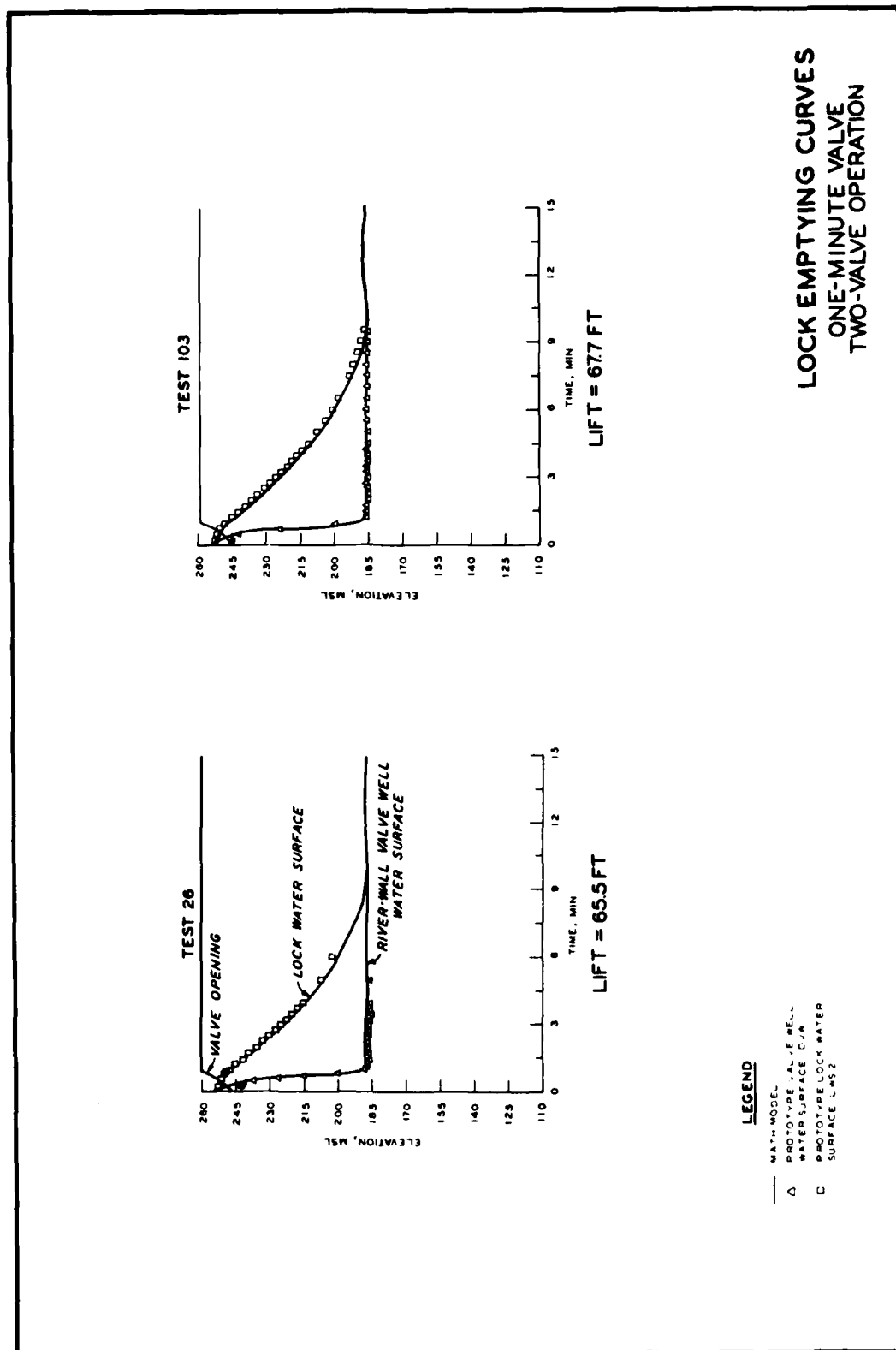
PROTOTYPE WATER SURFACE

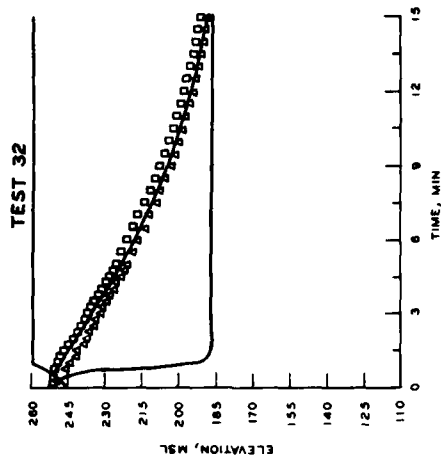
PROTOTYPE VALVE WELL WS EL

NOTE: SEE TABLE 2 FOR AIR VENT OPENINGS

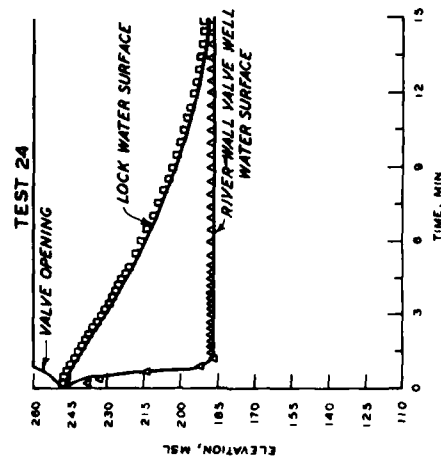
**WATER-SURFACE ELEVATIONS
AND CULVERT PRESSURES
ONE-VALVE FILLING OPERATION**

PLATE 4





LIFT = 65.4 FT



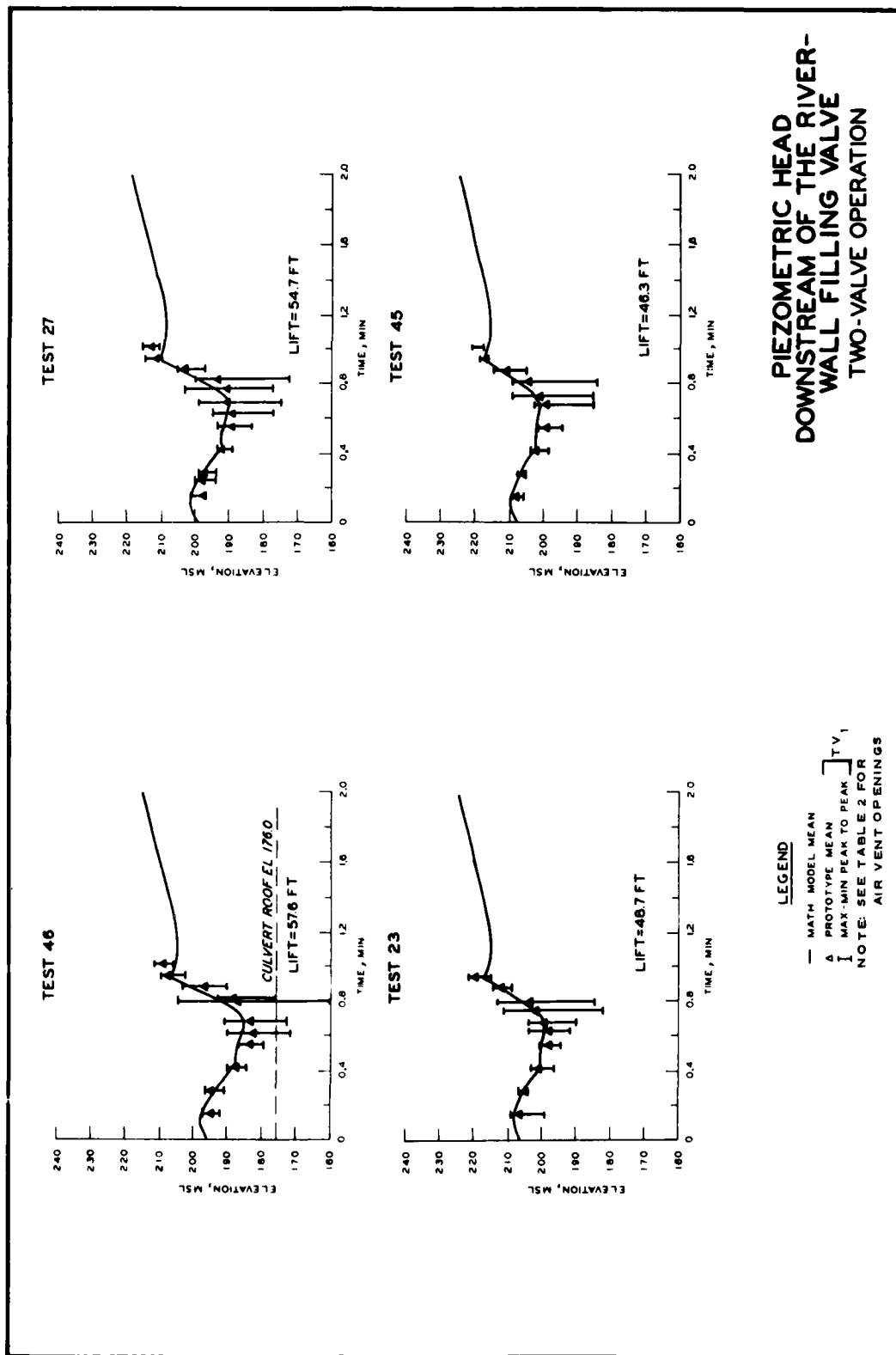
LIFT = 59.7 FT

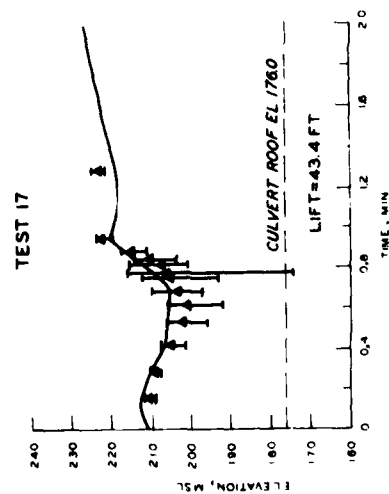
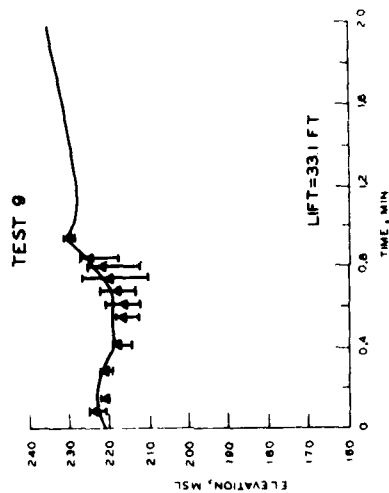
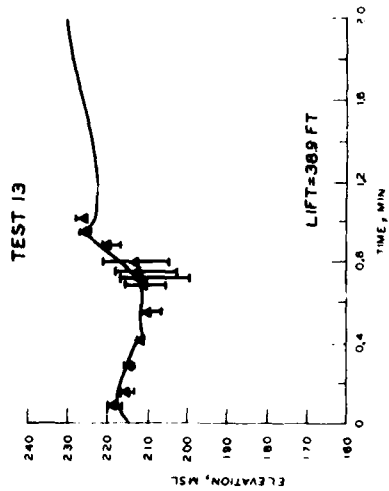
LEGEND

- MATH MODEL
- PROTOTYPE VALVE WELL
- WATER SURFACE DVM
- PROTOTYPE LOCK WATER SURFACE LWS 2

LOCK EMPTYING CURVES
ONE-MINUTE VALVE
ONE-VALVE OPERATION

PLATE 6





LEGEND

— MATH MODEL MEAN

Δ PROTOTYPE MEAN

□ MAX MIN PEAK TO PEAK TV

NOTE: SEE TABLE 2 FOR AIR VENT OPENINGS

PIEZOMETRIC HEAD
DOWNSTREAM OF THE RIVER-
WALL FILLING VALVE
TWO-VALVE OPERATION

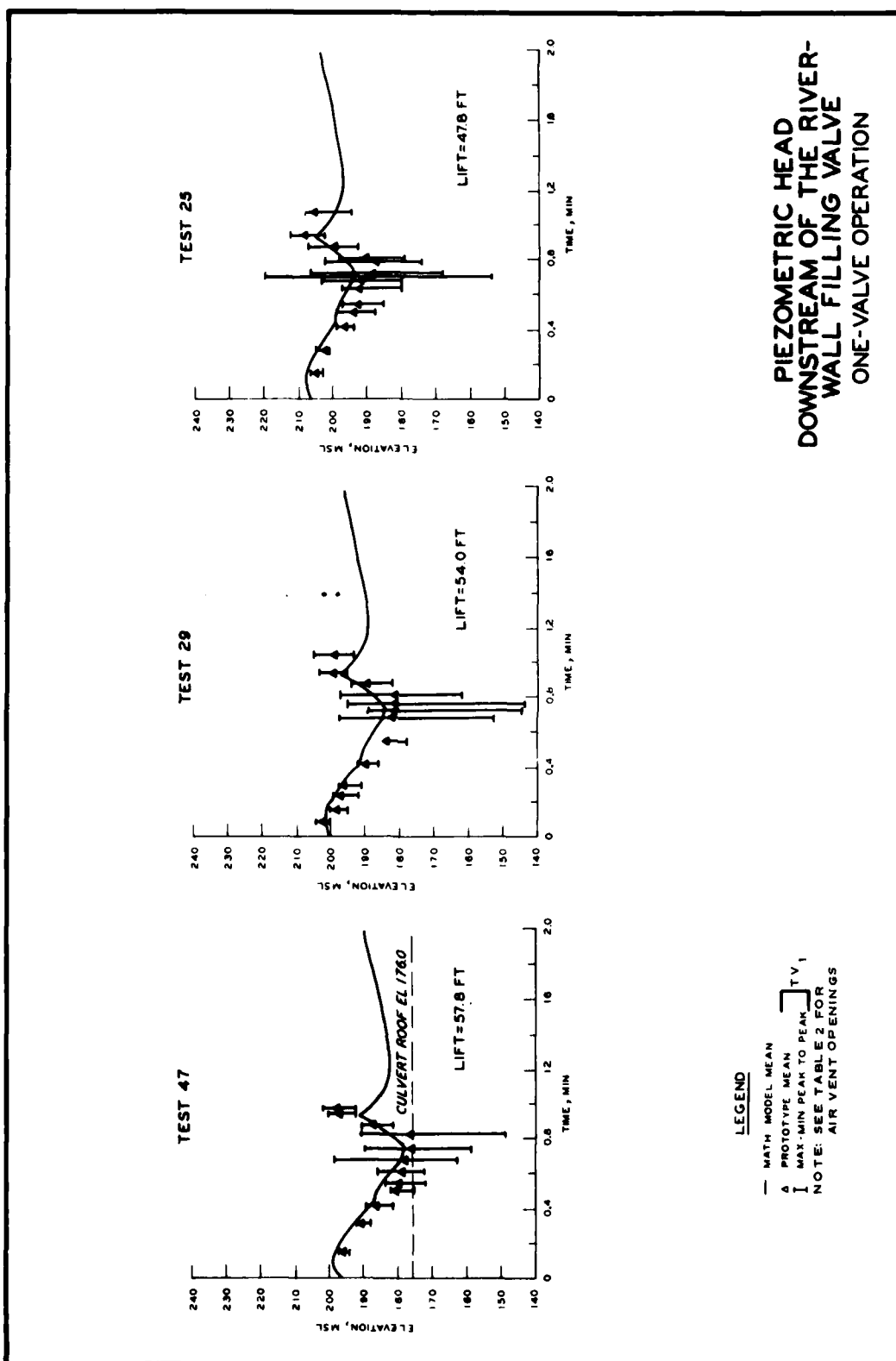
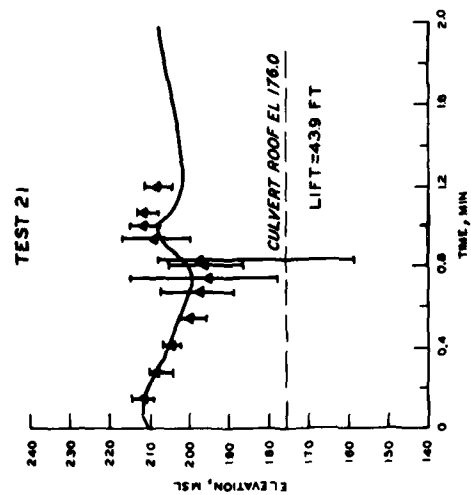
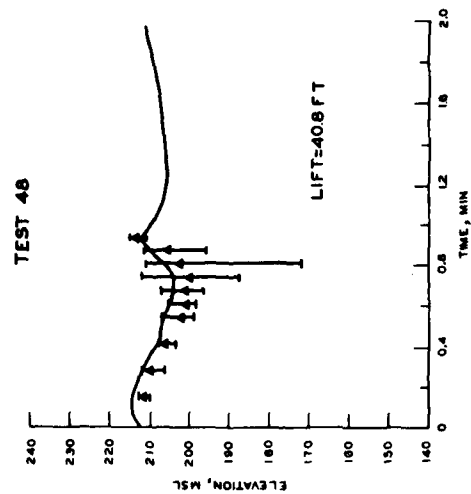
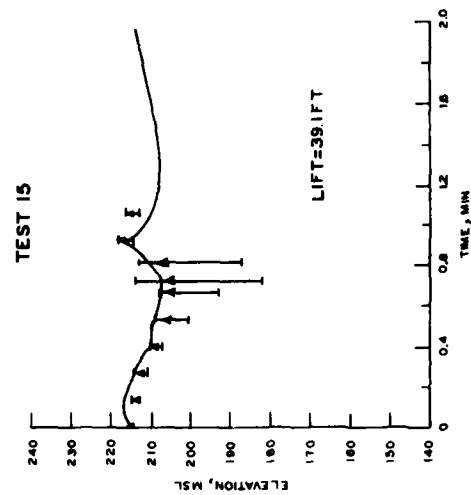


PLATE 8



LEGEND

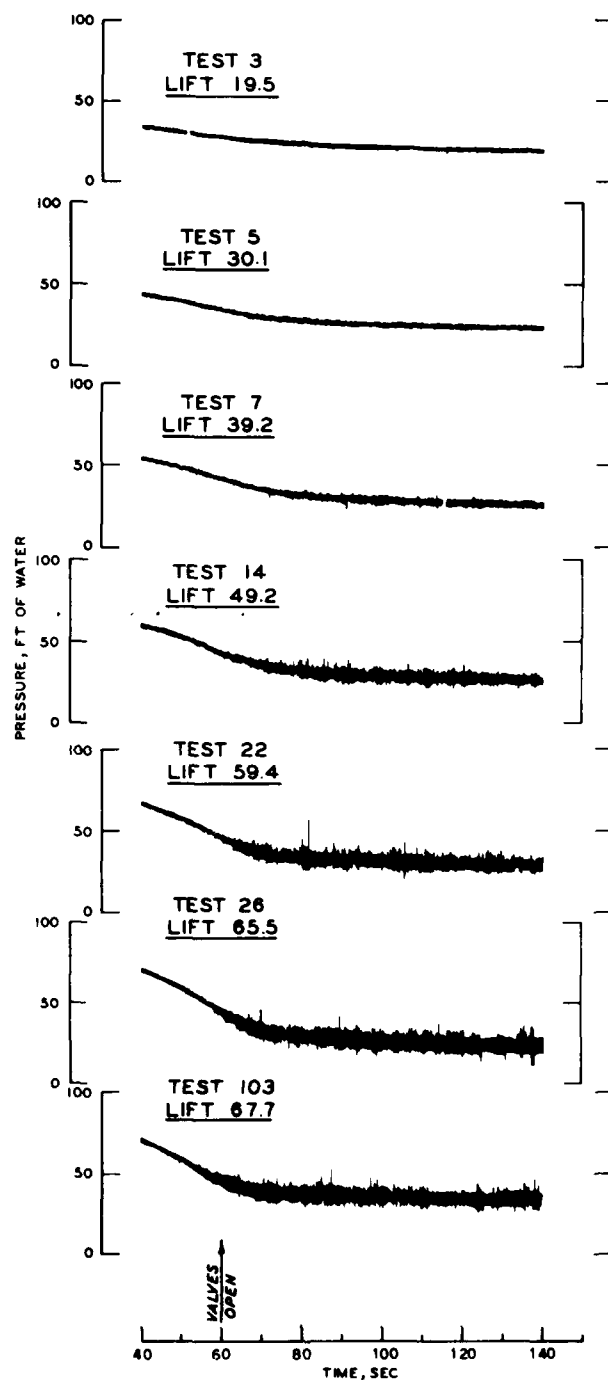
— MATH MODEL MEAN

Δ PROTOTYPE MEAN

⌈ MAX-MIN PEAK TO PEAK ⌋ TV₁

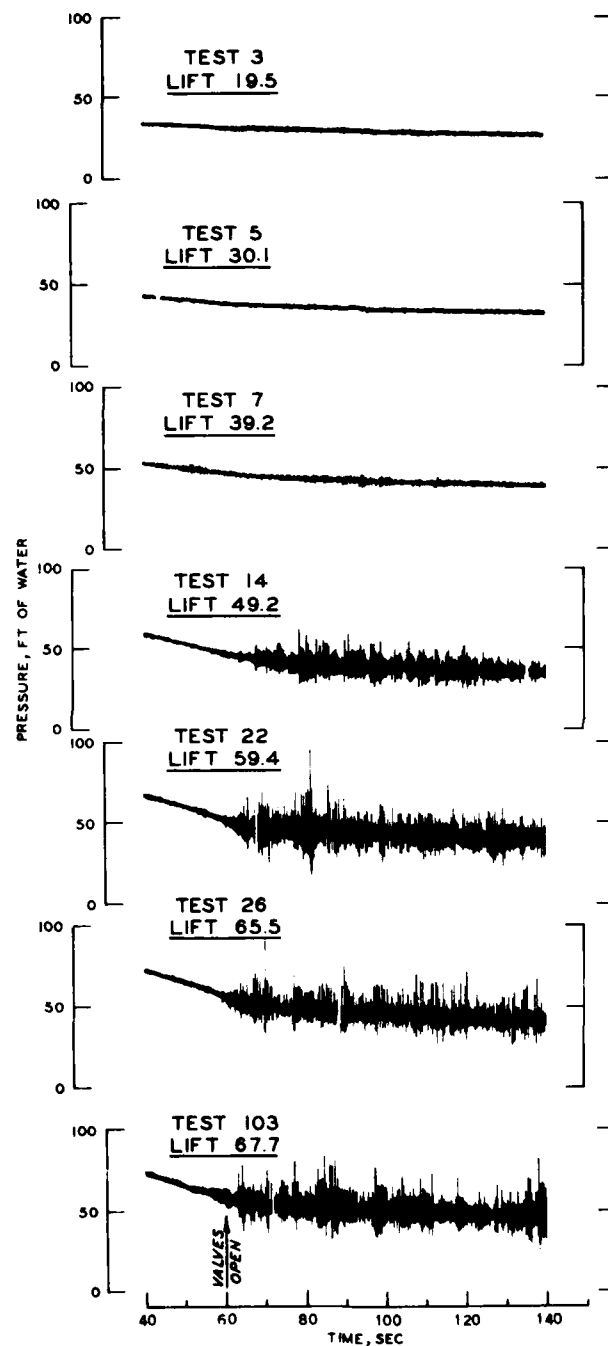
NOTE: SEE TABLE 2 FOR AIR VENT OPENINGS

PIEZOMETRIC HEAD
DOWNSTREAM OF THE RIVER-
WALL FILLING VALVE
ONE-VALVE OPERATION



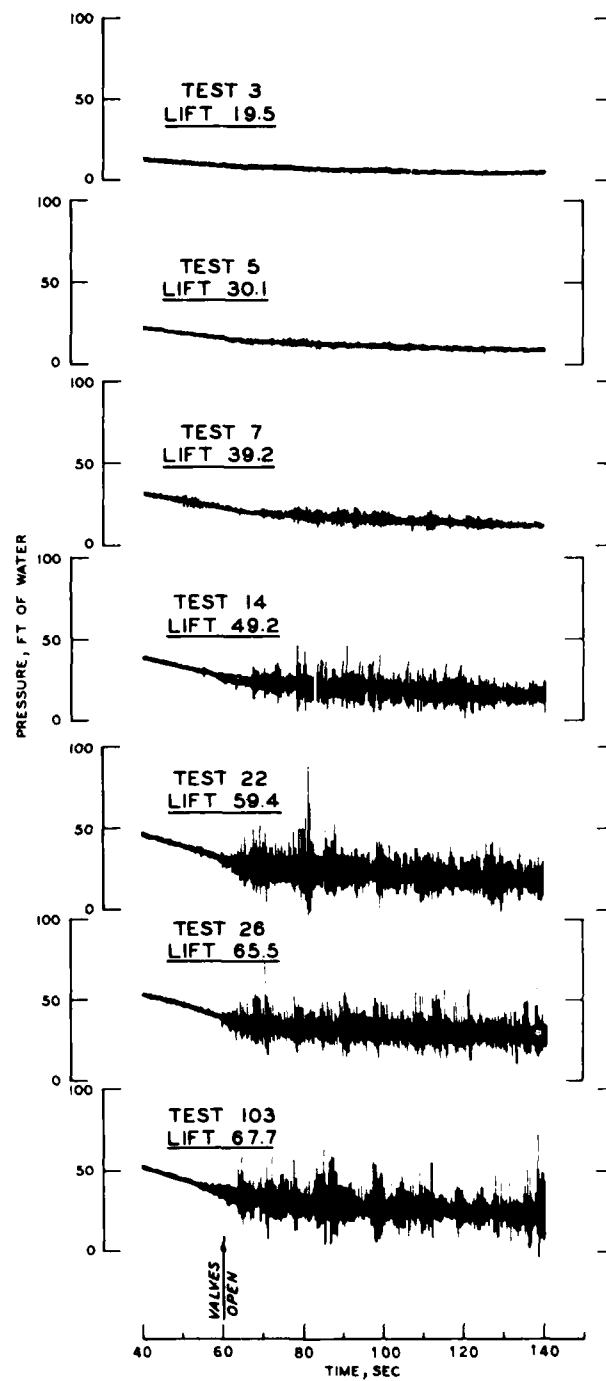
TESTING CONDITIONS
TWO-VALVE OPERATION
ONE-MINUTE VALVE TIME

TRANSDUCER TLI
EMPTYING OPERATION



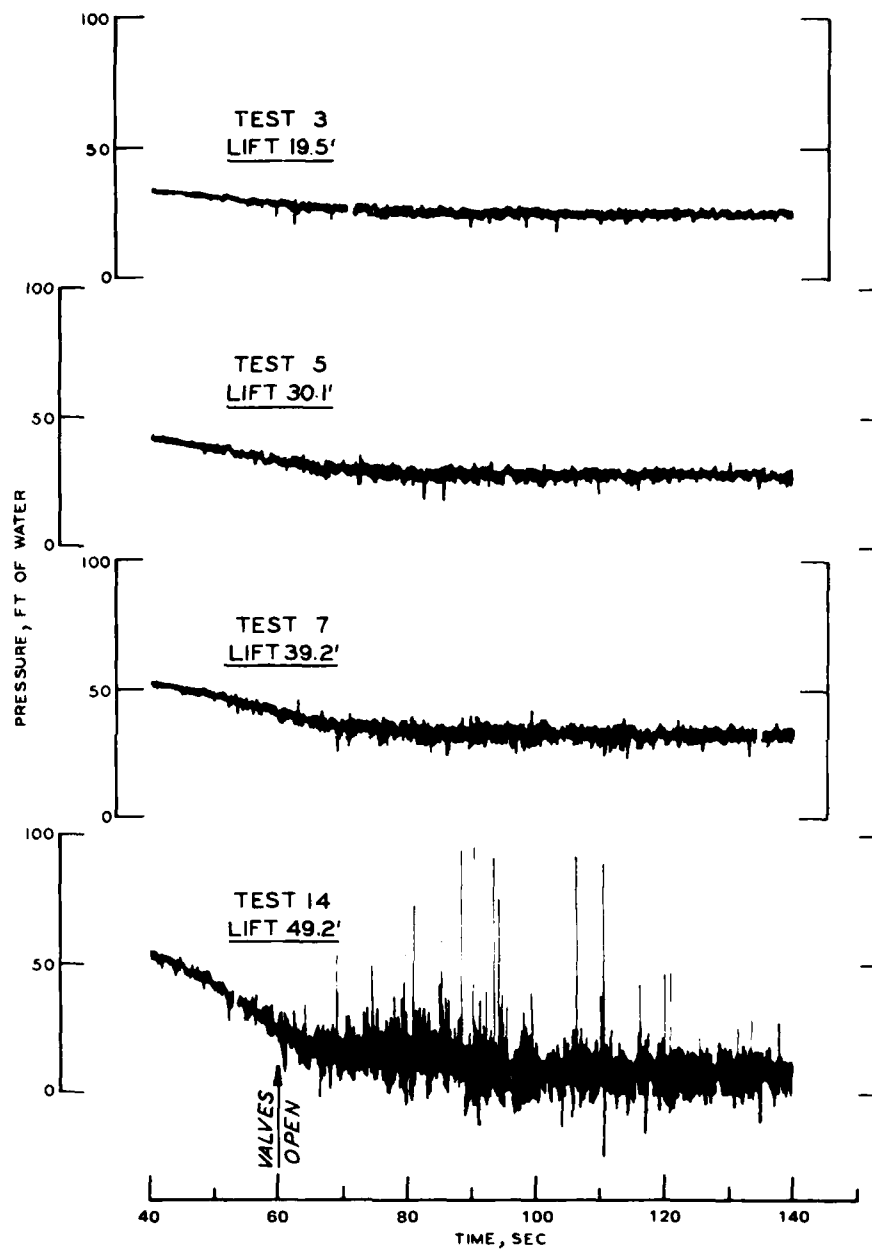
TESTING CONDITIONS
TWO-VALVE OPERATION
ONE-MINUTE VALVE TIME

TRANSDUCER TVI
EMPTYING OPERATION



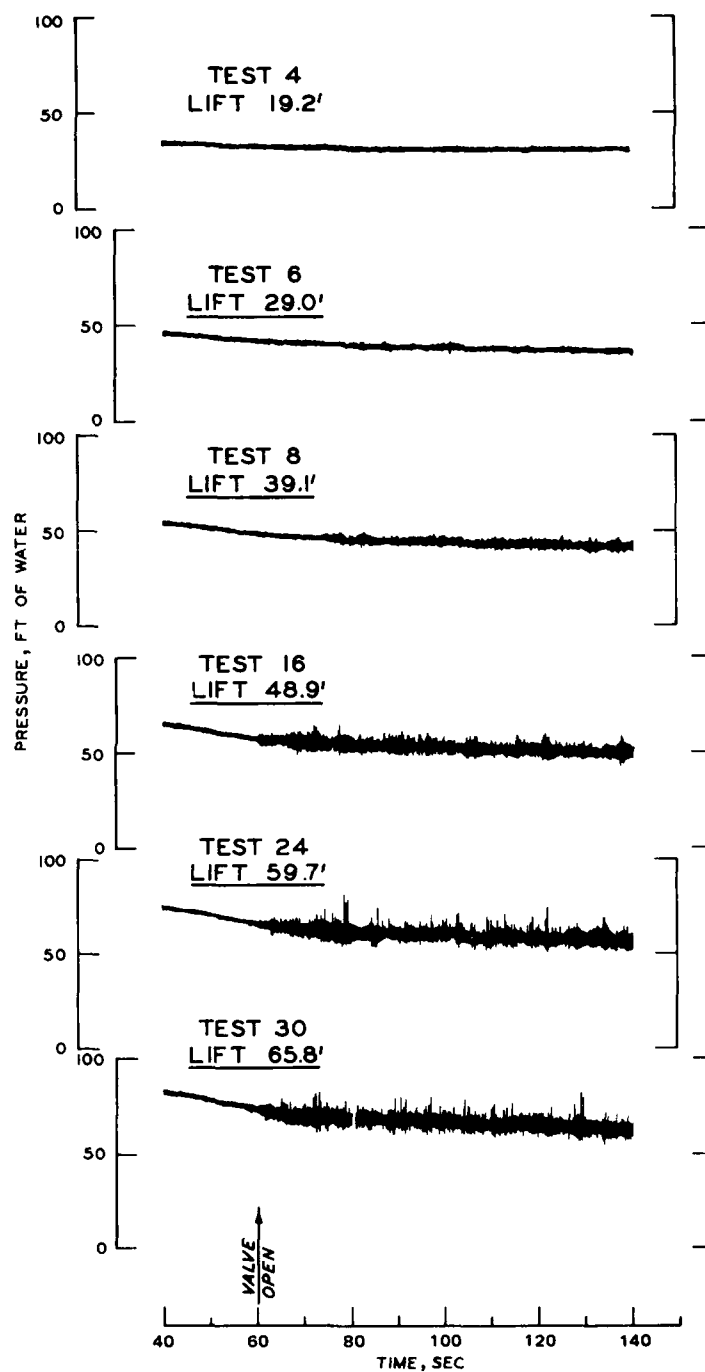
TESTING CONDITIONS
TWO-VALVE OPERATION
ONE-MINUTE VALVE TIME

TRANSDUCER TBI
EMPTYING OPERATION



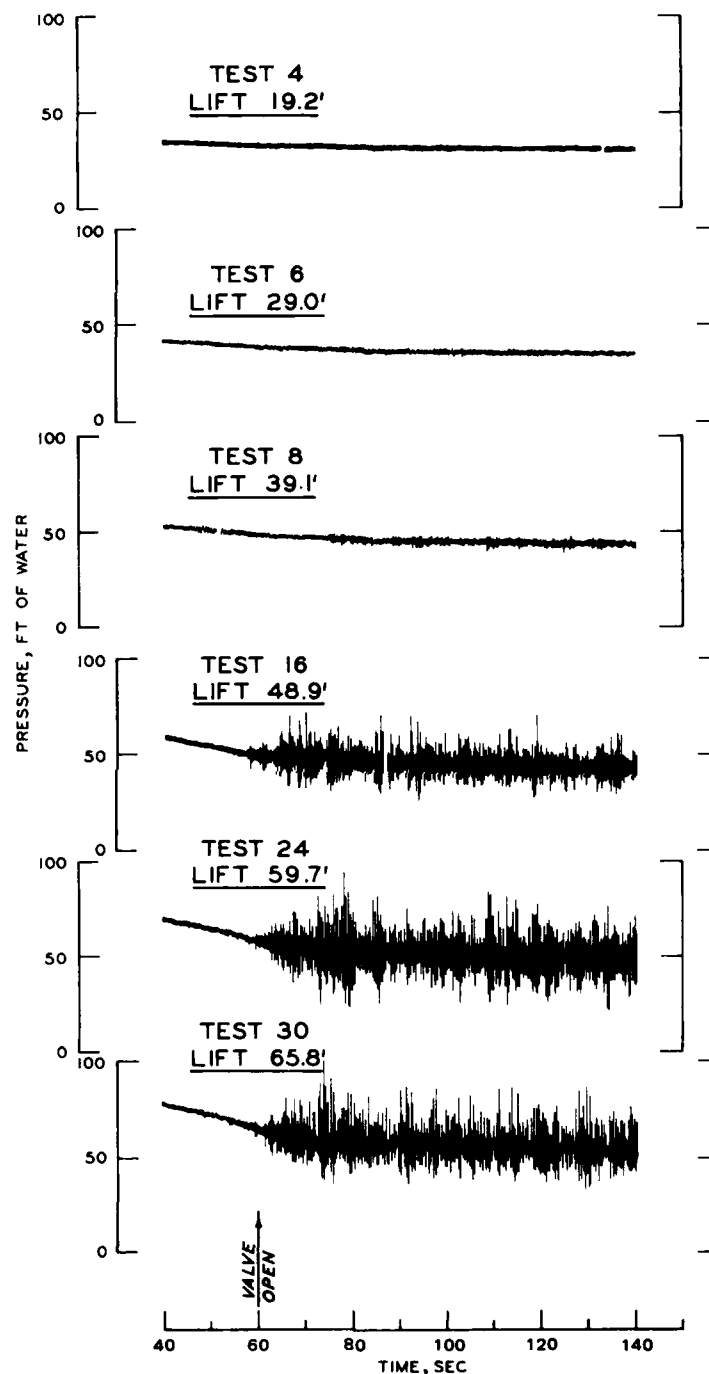
TESTING CONDITIONS
TWO VALVE OPERATION
ONE-MINUTE VALVE TIME

TRANSDUCER TCI
EMPTYING OPERATION



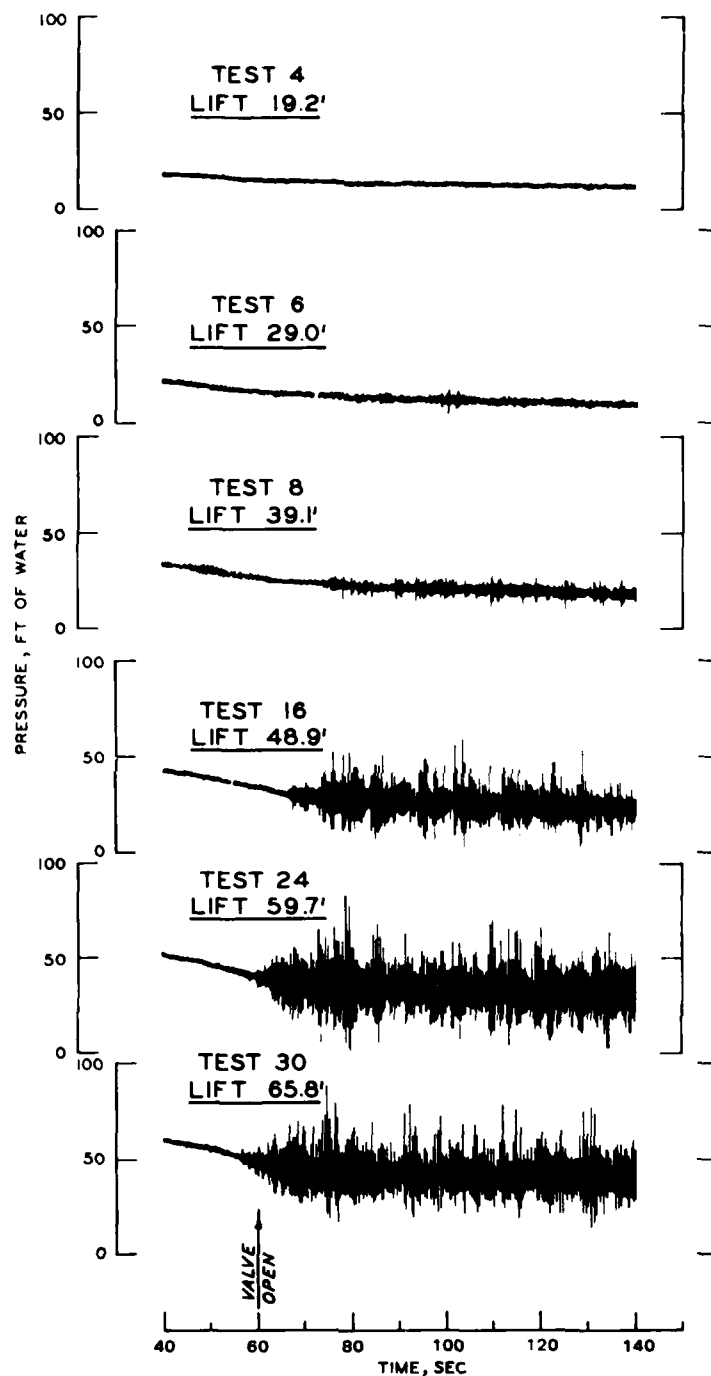
TESTING CONDITIONS
RIVER-WALL VALVE ONLY
ONE-MINUTE VALVE TIME

TRANSDUCER TLI
EMPTYING OPERATION



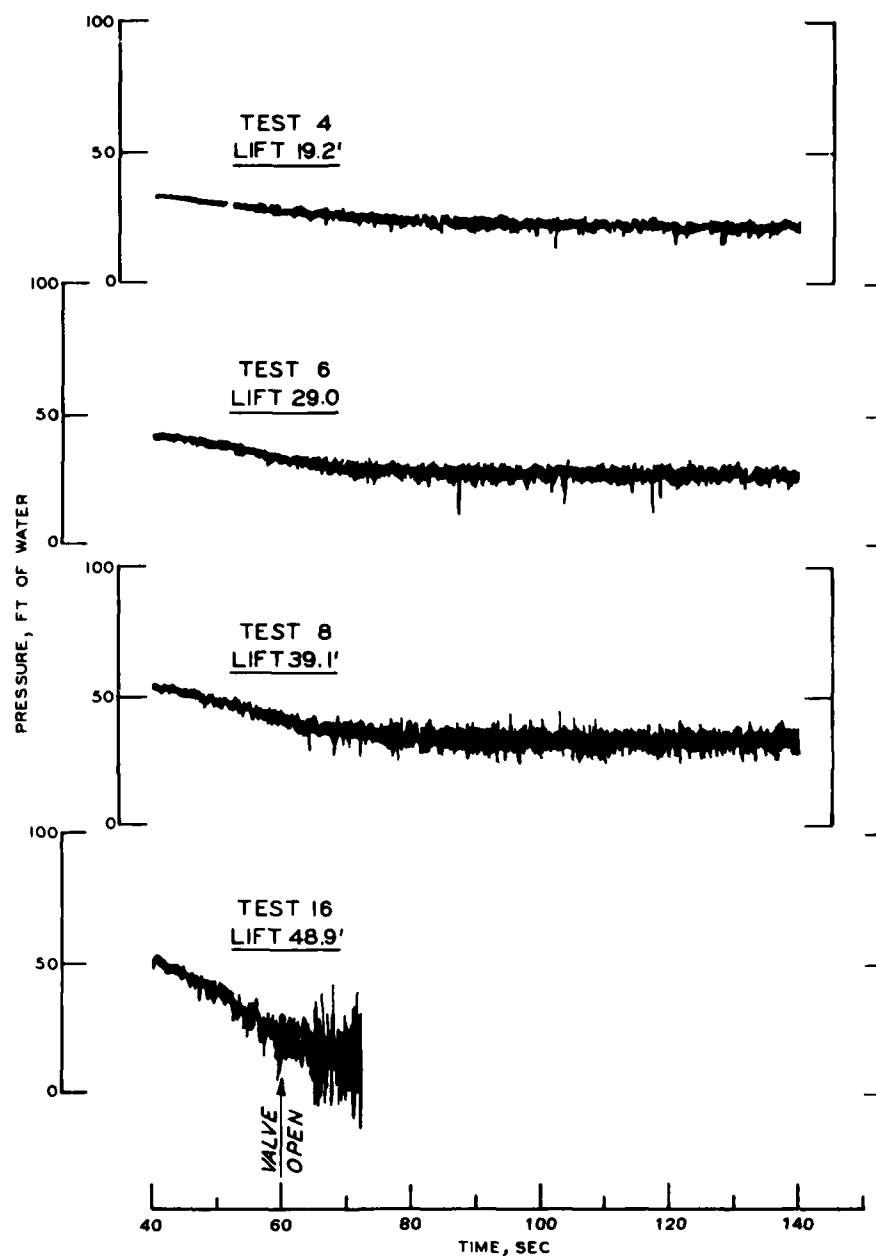
TESTING CONDITIONS
 RIVER-WALL VALVE ONLY
 ONE-MINUTE VALVE TIME

TRANSDUCER TVI
 EMPTYING OPERATION



TESTING CONDITIONS
RIVER-WALL VALVE ONLY
ONE-MINUTE VALVE TIME

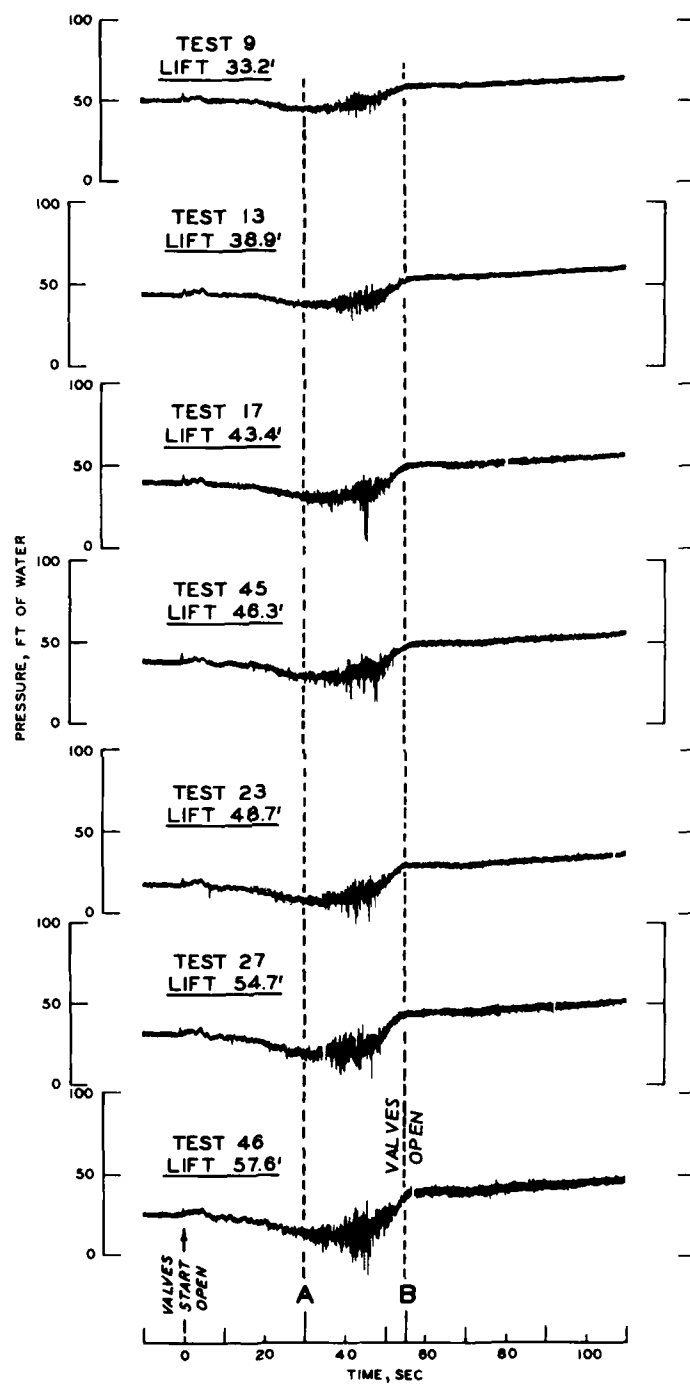
TRANSDUCER TBI
EMPTYING OPERATION



TESTING CONDITIONS

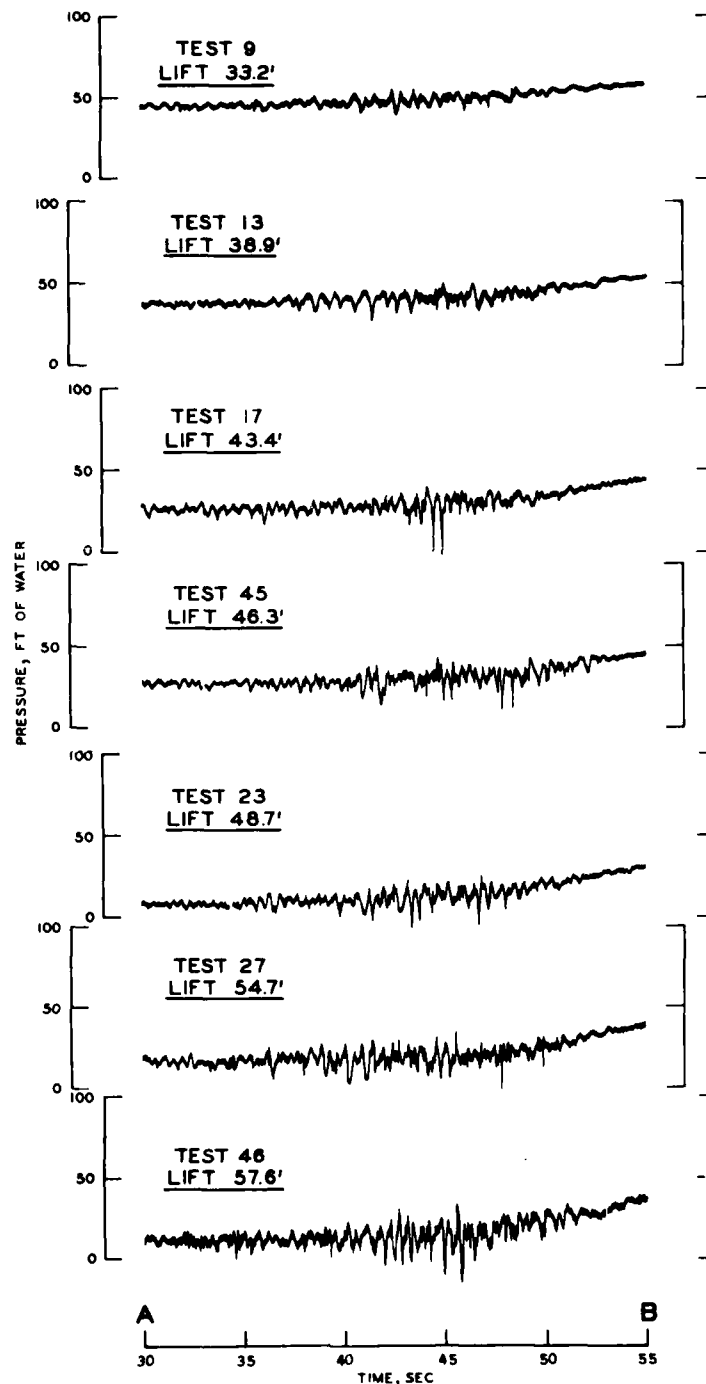
RIVER-WALL VALVE ONLY
ONE-MINUTE VALVE TIME

TRANSDUCER TCI
EMPTYING OPERATION



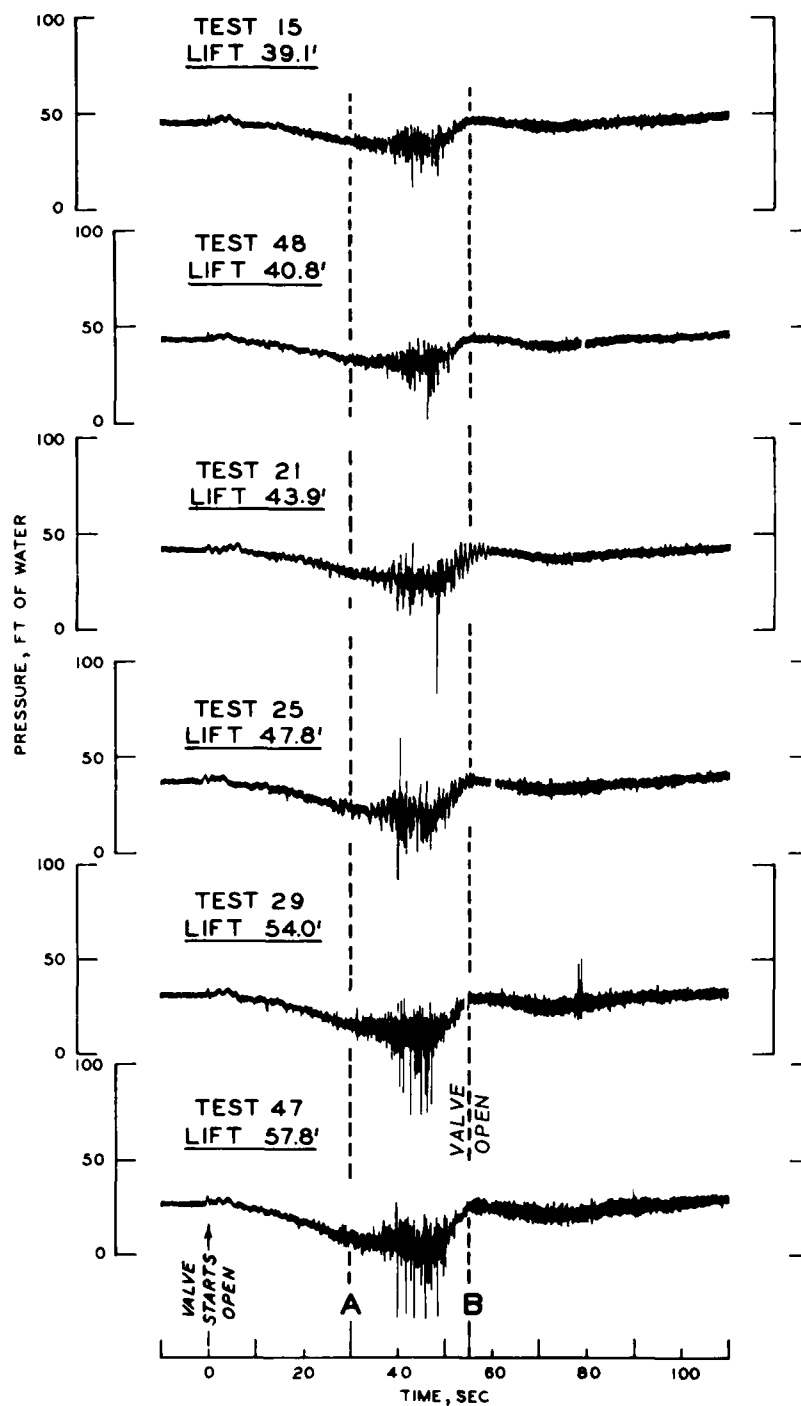
NOTE: SEE TABLE 2 FOR
AIR VENT OPENINGS

TRANSDUCER TVI
TWO-VALVE FILLING OPERATION
SLOW CHART SPEED



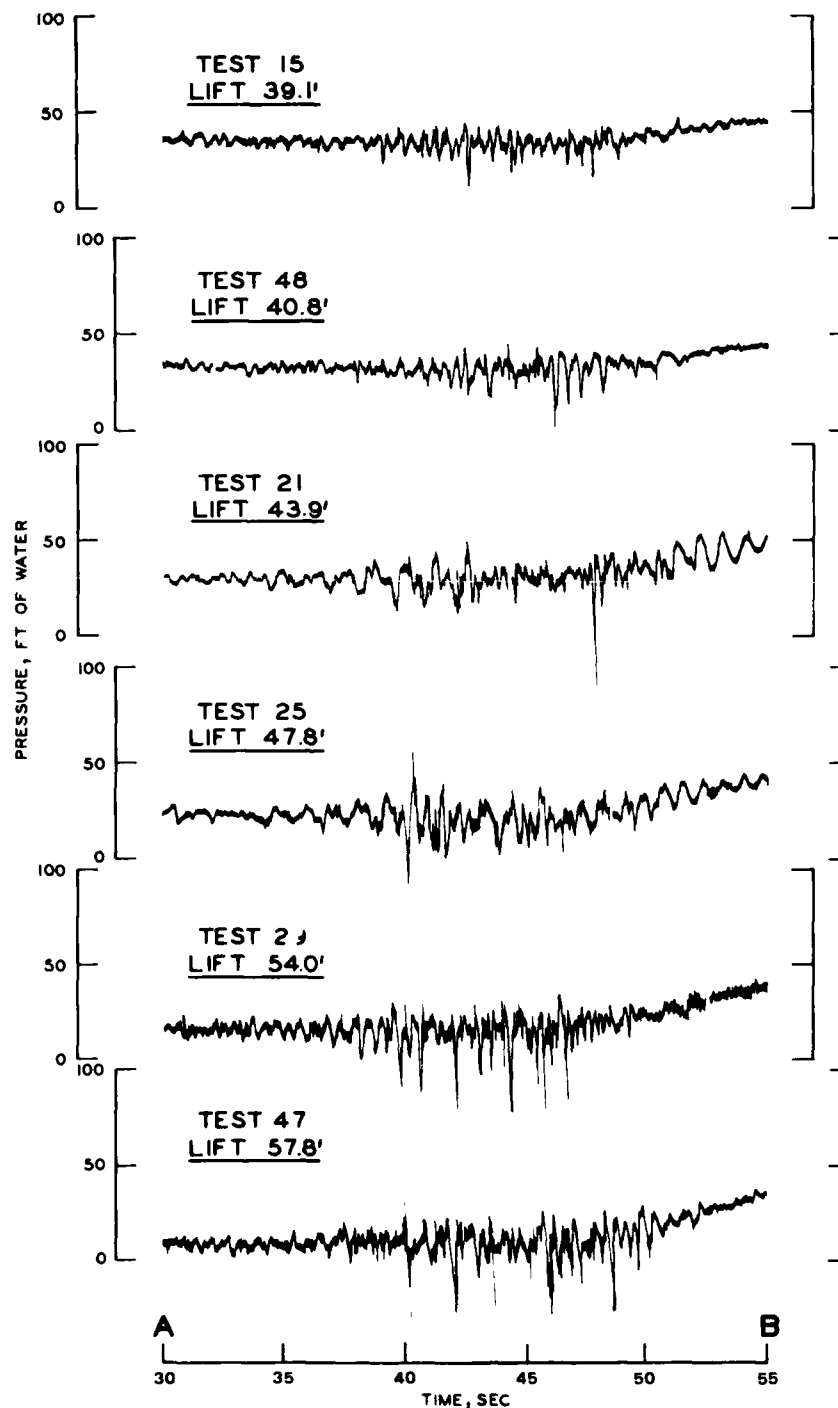
NOTE: SEE TABLE 2 FOR
AIR VENT OPENINGS

TRANSDUCER TVI
TWO-VALVE FILLING OPERATION
FAST CHART SPEED



NOTE: SEE TABLE 2 FOR AIR
VENT OPENINGS

TRANSDUCER TVI
ONE-VALVE FILLING OPERATION
SLOW CHART SPEED



NOTE: SEE TABLE 2 FOR AIR
VENT OPENINGS

TRANSDUCER TVI
ONE-VALVE FILLING OPERATION
FAST CHART SPEED

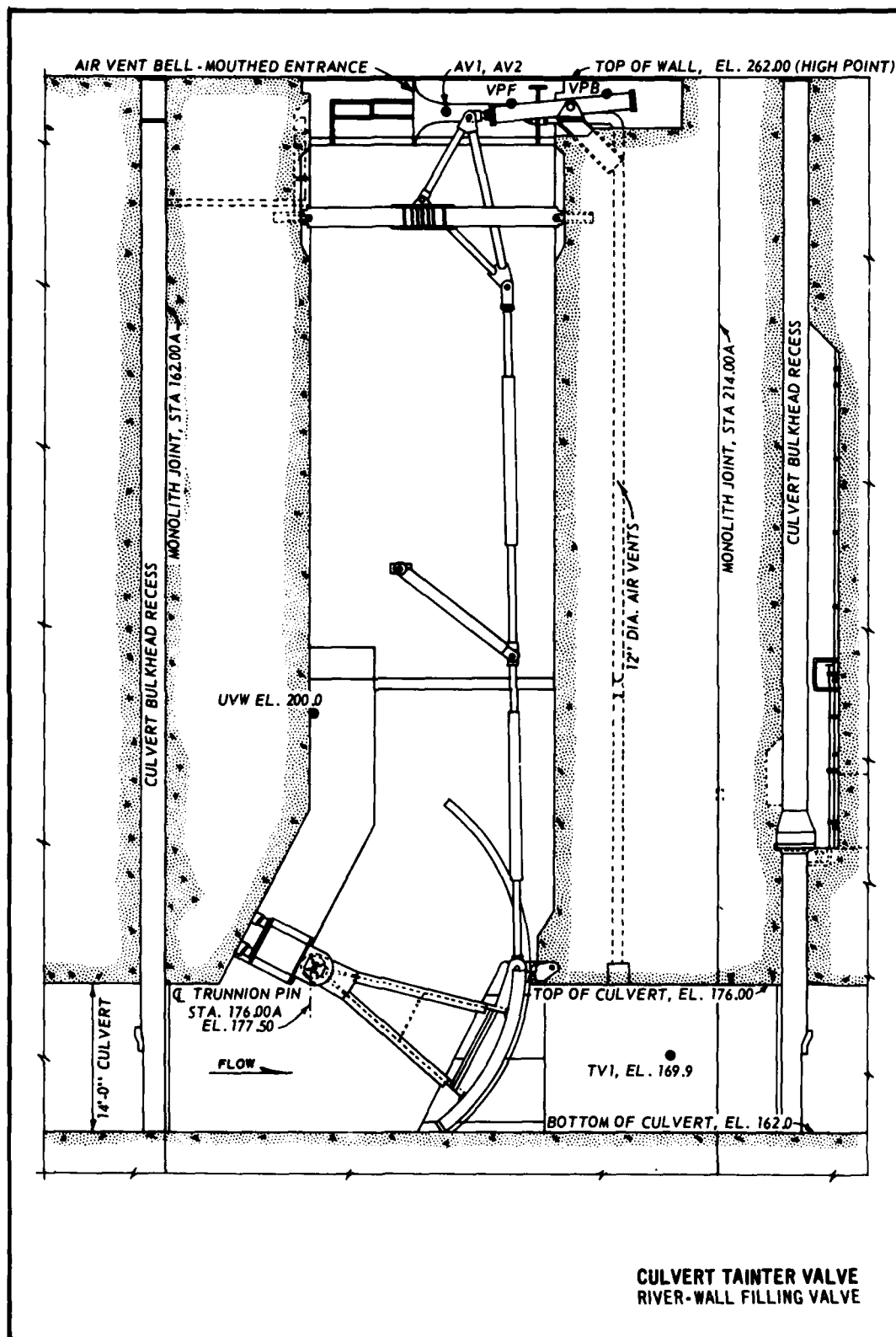
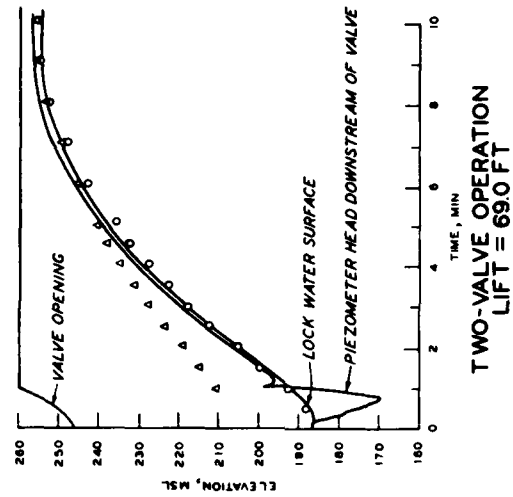
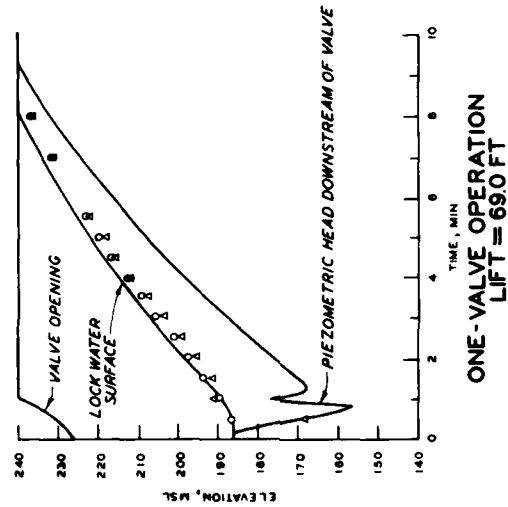


PLATE 22



LEGEND

- MATH MODEL ADJUSTED WITH PROTOTYPE DATA
- △ PHYSICAL MODEL PIEZOMETRIC PRESSURE
- DOWNSTREAM OF FILLING VALVE
- PHYSICAL MODEL LOCK WATER SURFACE

MATH AND PHYSICAL MODEL COMPARISON ONE-MINUTE VALVE

APPENDIX A: HYDRAULICS OF THE CULVERT SYSTEM (MODEL AND PROTOTYPE)

Introduction

Overview

1. A prototype lock is normally more efficient than its model; that is, the prototype fills (or empties) more rapidly than direct model predictions show. The difference in efficiency is acceptable as far as most of the modeled quantities are concerned (hawser forces, for example) and can be accommodated empirically for others (filling time and over-travel, specifically). However, in circumstances in which knowledge of extreme pressures within the culverts in the prototype is important, additional corrections to the predictions from the model are required. These corrections are particularly important for high-lift locks in which questions regarding cavitation (resulting from extremely low pressures) are of concern. The objective of this appendix is to identify and quantify the mechanism causing the difference in efficiency at Bankhead. Although the emphasis herein is placed on lock filling, the same principles apply to emptying.

Data sources

2. Information used in the subsequent paragraphs are from three specific sources.

- a. Bankhead Prototype - main text of this report (reference R1 herein) plus additional data reduction as required.
- b. Bankhead Model - WES Technical Report: (Reference R2.)
Oswalt, N. R., Ables, J. H., Jr., & Murphy, T. E.,
"Navigation Conditions and Filling and Emptying System,
New Bankhead Lock, Black Warrior River, Alabama, Hydraulic
Model Investigation, T. R. H-72-6, Sep 1972, U. S. Army
Engineer Waterways Experiment Station, CE, Vicksburg, MS.
- c. Analytical Description - WES Miscellaneous Paper:
(Reference R3.) Hebler, Martin T. and Neilson, F. M.,
"Lock Filling and Emptying - Symmetrical Systems," M. P.
H-76-13, June 1976, U. S. Army Engineer Waterways Experiment
Station, CE, Vicksburg, MS.

Scale ratios

3. The lock model is constructed geometrically similar to the

prototype; the scaling procedure assumes similar flow patterns in model and prototype so that Eulerian scale ratios apply, i.e.

$$\left(\frac{\Delta h}{\frac{v^2}{2g}} \right)_{\text{Model}} = \left(\frac{\Delta h}{\frac{v^2}{2g}} \right)_{\text{Prototype}} \quad (A1)$$

where

Δh = difference in piezometric head between two locations in the culvert

V = reference velocity

Boundary conditions for a lock culvert model require that Δh from upper pool to lock chamber also be geometrically similar in model and prototype. For practical reasons, the acceleration due to gravity (g), and the kinematic viscosity (ν) and unit weight (γ) of the fluid (water) are taken to be invariant and the following scaling ratios are used.

Quantity	Dimension (F-L-T)	Scale Ratios	
		Evaluation	Bankhead (Model:Prototype)
Distance	L	λ_l	1:25
Area	L^2	$\lambda_{ll} = \lambda_l^2$	1:625
Volume	L^3	$\lambda_{lll} = \lambda_l^3$	1:15,625
Piezometric head, Δh	L	$\lambda_h = \lambda_l$	1:25
Velocity	$L T^{-1}$	$\lambda_v = \lambda_l^{1/2}$	1:5
Discharge	$L^3 T^{-1}$	$\lambda_q = \lambda_l^{5/2}$	1:3125
Time	T	$\lambda_t = \lambda_l^{1/2}$	1:5
Acceleration	$L T^{-2}$	$\lambda_a = 1$	1:1
Force	F	$\lambda_F = \lambda_l^3$	1:15,625
Pressure	$F L^{-2}$	$\lambda_p = \lambda_l$	1:25
Reynold's number	--	$\lambda_R = \lambda_l^{3/2}$	1:125
Froude number	--	$\lambda_F = 1$	1:1

4. The 1:1 Froude scaling is appropriate for studying the surge condition upstream of the lock and to the oscillations within the lock chamber; on the other hand, the large difference in Reynolds numbers (and possibly relative roughness) is a deficiency as far as conditions within the culverts are concerned.

Relative Efficiencies

5. A convenient comparison of the model and prototype efficiencies is by means of the traditional empirical lock design equation (Pillsbury's equation):

$$T - Kt_v = \frac{2 A_L (\sqrt{H+d_o} - \sqrt{d_o})}{n A_c C_L \sqrt{2g}} \quad (A2)$$

where

T = lock filling time, sec

K = overall valve coefficient

t_v = valve time, sec

A_L = chamber surface area, 73,700 ft²

H = initial head, ft; i.e., lift

d_o = overtravel, ft

n = number of valves used (1 or 2)

A_c = culvert area, 196.0 ft²

C_L = overall lock coefficient

g = acceleration due to gravity, 32.2 ft/sec²

6. Equation A2 is based on a solution for lock filling in which inertial effects are initially neglected--the overtravel is incorporated into the final solution (in the manner shown in Equation A2) to approximately accommodate the inertial effects. For the Bankhead model tests, the filling time for instantaneous valving is obtained by linear extrapolation to $t_v = 0$ on a T versus t_v plot as shown in Figure A1. Since the initial head, H , and overtravel, d_o , are essentially constant for each line, the overall valve coefficient (also a constant) is

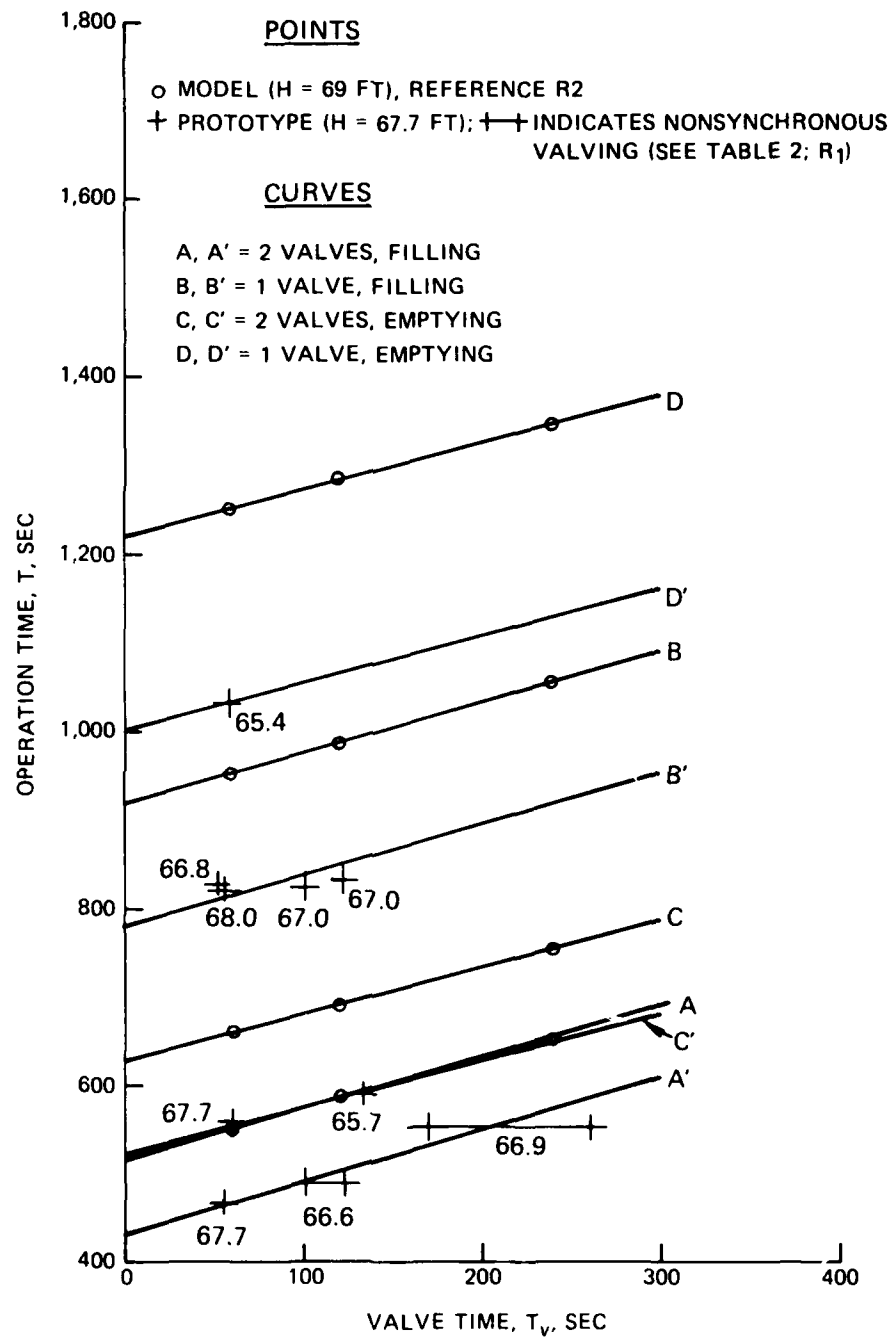


Figure A1. Operation time (model and prototype)

the slope of the line. The lock coefficient is evaluated by means of Equation A2 using conditions for $t_v = 0$. The prototype data are so limited in number (and contain effects due to nonsynchronous valving and variations in initial head) that evaluation of both K and C_L are precluded. Therefore, the calculations here assume that the overall valve coefficient K is the same in the prototype as in the model; hence the extrapolation shown in Figure A1 can be accomplished and C_L computed as in the model tests by means of Equation A2. The results are:

Condition	Model (M) or Proto- type (P)	H ft	d_o ft	T for $t_v = 0$ sec	K	C_L	Percent Change Prototype Rel to Model	
							C_L	$T - Kt_v$
1. Two valves, filling	M	69	1.05	516	0.57	0.67		
	P	67 ^a	1.4 ^b	432	--	0.77	+15	-14
2. One valve, filling	M	69	0.5 ^c	920	0.56	0.78		
	P	67.5 ^a	0.7 ^b	780	--	0.89	+14	-14
3. Two valves, emptying	M	69	0.63	628	0.52	0.56		
	P	66.7 ^a	1.2 ^b	522	--	0.64	+14	-16
4. One valve, emptying	M	69	0.32 ^c	1220	0.53	0.60		
	P	65.4 ^a	0.6 ^c	1000	--	0.69	+15	-15

Notes: a. These are mean values for the tests shown in Figure A1.
b. The miter gates opened before overtravel was complete; these are maximum observed values for the listed conditions.
c. These values are one-half of the ones observed during 2-valve operation.

7. As shown in the above listing the prototype fills and empties about 14 percent faster (with instantaneous valving) than the model; this is only slightly faster than the 5 to 11 percent given as an estimate in the model report.

Equations Describing Lock Filling

8. The following summary of equations (Reference R3) relating to lock filling also applies to emptying provided appropriate sign changes are included. Basically, the overall headloss in the system is considered to be made up of five manageable components as shown in Figure A2;

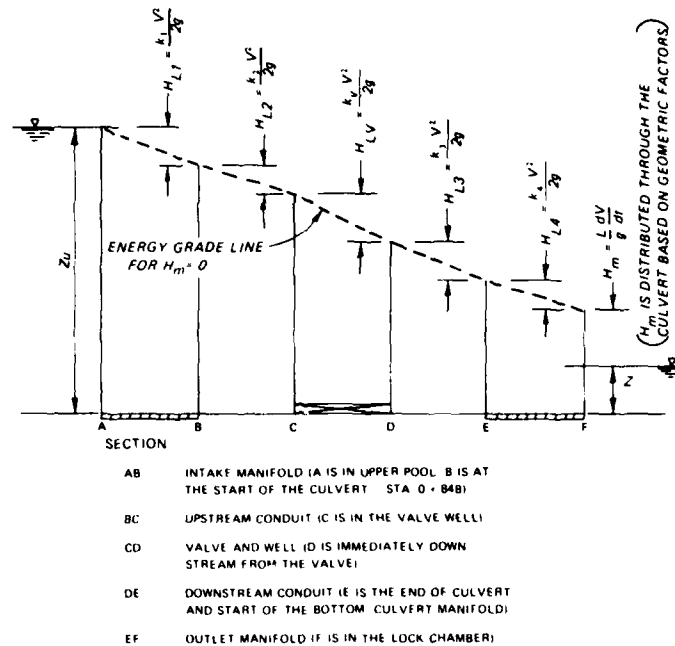


Figure A2. Schematic of the lock chamber

<u>Component</u>	<u>Head Loss</u>	
Intake	$H_{L1} = k_1 \frac{V^2}{2g}$	(a)
Upstream conduit	$H_{L2} = \frac{k_2 V^2}{2g}$	(b)
Valve and valve well	$H_{Lv} = \frac{k_v V^2}{2g}$	(c) (A3)
Downstream conduit	$H_{L3} = \frac{k_3 V^2}{2g}$	(d)
Outlet	$H_{L4} = \frac{k_4 V^2}{2g}$	(e)

where V is the average velocity at a reference location in the culvert (normally just downstream of the filling valve). The overall loss, H_{Lt} , is

$$H_{Lt} = (k_1 + k_2 + k_v + k_3 + k_4) \frac{V^2}{2g} \quad (a)$$

or

(A4)

$$H_{Lt} = \frac{k_t V^2}{2g} \quad (b)$$

Coefficients k_1 , k_v , and k_4 are taken to be entirely form-dependent; coefficients k_2 and k_3 are not only affected by form but also by Reynolds number and relative roughness. However, in view of the "stubby" conduits and the dominance of form effects in a lock system, the conduit coefficients k_2 and k_3 can reasonably be assumed constant for either model or prototype--bearing in mind that significant differences may exist between the model and the prototype values.

9. Since the flow is incompressible, the inertial effect is treated as a lumped quantity; that is

$$H_m = \frac{L_m}{g} \frac{dV}{dt} \quad (A5)$$

where

H_m = overall inertial effect

L_m = inertial length coefficient

$$L_m = A_c \sum_{i=1}^m \frac{L_i \alpha_i}{A_i} \quad (A6)$$

for a conduit made up of m sections of lengths, L_i ; areas, A_i ; and flow ratios, α_i (i.e., $\alpha_i = Q_i/Q$ where Q_i is the flow through the i^{th} section).

10. The water-surface differential, $Z_u - z$ in Figure A2, is the

sum of the inertial effect (Equation A5) and the energy losses (Equation A4) or:

$$\frac{k_t V^2}{2g} = (Z_u - z) - \frac{L_m}{g} \frac{dV}{dt} \quad (A7)$$

11. Continuity applies to the culvert flow ($n A_c V$) and the rate-of-rise, $A_L dz/dt$, of the lock chamber water surface

$$V = \frac{A_L}{n A_c} \frac{dz}{dt} \quad (A8)$$

and

$$\frac{dV}{dt} = \frac{A_L}{n A_c} \frac{d^2 z}{dt^2} \quad (A9)$$

12. Integration of Equation A7 (with $k_t = \text{constant}$ and for reasonably high lifts)

$$\frac{dV}{dt} \approx \frac{-gn A_c}{k_t A_L} \quad (a)$$

or

$$k_t \approx \frac{-g \left(\frac{n A_c}{A_L} \right)^2}{\frac{d^2 z}{dt^2}} \quad (b) \quad (A10)$$

13. Similarly, for overtravel,

$$d_o \approx \frac{L_m n A_c}{k_t A_L} \quad (a)$$

or

$$L_m \approx \frac{d_o k_t A_L}{n A_c} \quad (b) \quad (A11)$$

Since the possible measurement error for d_o is always large, Equation A11(b) is not an appropriate means of evaluating L_m .

Data Reduction - L_m

14. The inertia coefficient, L_m , is based on culvert geometry (rather than test data); the Bankhead system is approximated by two sections. The value of L_m is calculated, Equation A6, as follows:

<u>Operation</u>	<u>Section i</u>	<u>L_i ft</u>	<u>A_i^2 ft²</u>	<u>α_i</u>	<u>L_m ft</u>
Filling	1	412	196	1.0	549
	2	140	100	0.5	
Emptying	1	140	100	0.5	563
	2	426	196	1.0	

Note in Plate 1 that in emptying, the landwall culvert is about 110 ft longer than the river-wall culvert; the smaller value is used.

Overall Loss Coefficient

Overview

15. During filling, both the increasing lock chamber water-surface level and the decreasing velocity in the culverts tend to raise pressures (hence to reduce cavitation potential) following valve fully open; conversely, during emptying, decreasing water-surface levels tend to oppose the effects of the decreasing velocity so as to prolong periods of low pressure (and possible cavitation). The Bankhead prototype lock experiences cavitation during emptying following valve fully open--this cavitation is an additional flow restriction which is not addressed herein. Therefore, loss coefficients during emptying are also not evaluated here. Three methods of determining k_t from experimental data are:

1. Steady flow: whenever dV/dt equals zero and $Z_u - z$ and Q are known, then k_t can be calculated directly from Equation A7 (or A4).
2. Numerical integration: whenever the valve time is short as compared with filling time, and the filling time is known, then k_t can be evaluated by successive trial integrations of Equations A7 and A9.
3. Rate-of-rise: whenever rate-of-rise, dz/dt , is known V can be calculated (Equation A8); similarly the slope

of a linear best-fit to a series of dz/dt measurements provides a dV/dt value by means of Equation A9. The value of k_t can then be calculated by means of Equation A10(b).

Each method has deficiencies in practice; the one actually used should, first, use the most precise measurements available, and, second, use data for test conditions (Reynolds numbers, IR) most appropriate to the ultimate use of k_t .

Model values (original design)

16. Steady-flow data for this design are presented in Reference R2; model quantities and calculated k_t values (method 1) are:

Q cfs	$Z_u - z$ ft	V fps	$IR = \frac{VD}{v}$; $D = 0.56$ ft	k_t
2.36	1.14	7.84	$4.4 (10^5)$	2.34

Model values (recommended design)

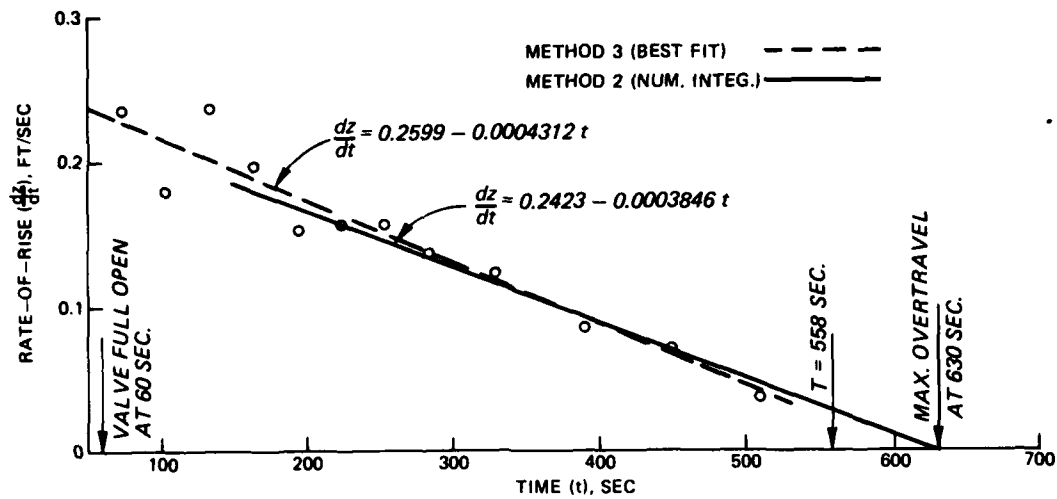
17. The limited accuracy and long sampling period in the model preclude accurate results using method 1. Values of IR and k_t are therefore obtained via methods 2 and 3; the measured model quantities and results are:

Operation	Lift ft	T min	IR		k_t	
			Max	@ T	Method 2	Method 3
Filling (2 valves)	2.76	1.86	$4.5(10^5)$	$6.5(10^4)$	2.37	2.11
Filling (1 valve)	2.76	3.06	$5.6(10^5)$	$6.7(10^4)$	1.61	1.45

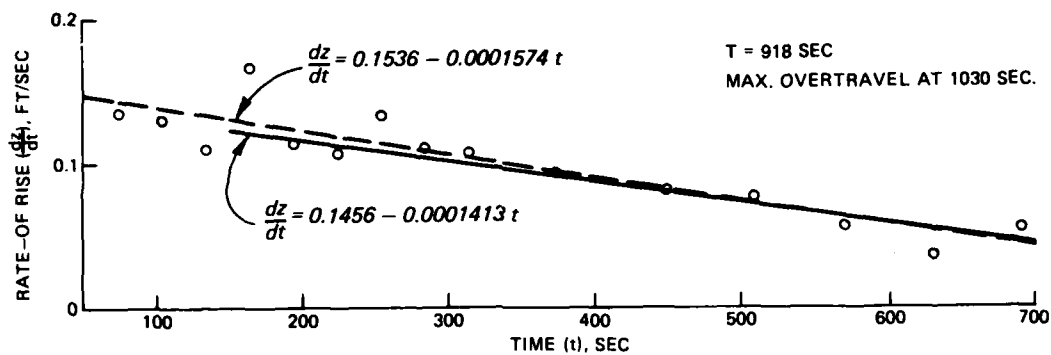
As these tests show in Figures A3a and A3b, respectively, the least-mean-square best-fit curves to the model data (method 3) and the calculated relations for dz/dt based on numerical integration (method 2) are both reasonable interpretations of the model data. The values of k_t calculated by method 2 are the more acceptable overall since the filling time and time of maximum overtravel do agree with measured values; on the other hand, values obtained using method 3 are more appropriate near higher model Reynolds numbers.

Prototype (method 1)

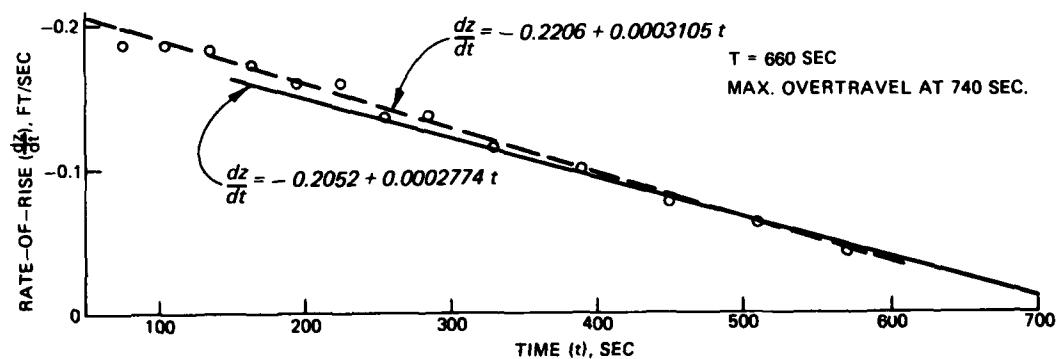
18. Since dV/dt equals zero, and Q and $Z_u - z$ are known,



a. TWO-VALVE FILLING OPERATION



b. SINGLE-VALVE FILLING OPERATION



c. TWO-VALVE EMPTYING OPERATION

Figure A3. Rate-of-rise (model data; prototype scales)

shortly after the valve is fully open, k_t can be evaluated directly from Equation A7. The following calculations use an average value for V during a 40-sec period following valve fully open; the value of $Z_u - z$ is at 80 sec from the start of each test. The listed tests have 1-min valving and higher lifts (greater than 40 ft). Since the averaging period is relatively short (i.e., comparable to the period of lock chamber water-surface oscillations) and the velocity variations relatively large, the coefficient evaluated here, k_t , is expected to be less reliable than a value obtained by means of method 2 or 3. During emptying tests (see main text) some flow restriction due to cavitation in the culvert system is expected; therefore, the emptying k_t values are not calculated.

Condition	Test	Initial Lift ft	V ft/sec	$Z_u - z$ ft	k_t
Filling (2 valves)	17	43.4	35.8	34.8	1.747
	23	48.7	39.1	40.4	1.699
	27	54.7	45.2	44.4	1.400
	34	63.0	45.1	53.5	1.694
	31	67.7	45.9	57.0	1.742
					Avg = 1.66
Filling (1 valve)	15	39.1	41.9	34.6	1.270
	21	43.9	43.2	39.5	1.360
	29	54.0	49.0	48.7	1.306
	44	63.3	50.6	57.3	1.441
	33	68.0	55.8	61.5	1.271
	35	66.8	56.4	60.5	1.230
					Avg = 1.31

Prototype (method 2)

19. Values of R and k_t obtained by means of numerical integration for selected prototype filling tests are:

Operation	Test	Lift ft	T min	R		k_t
				Max	@ T	
Filling (2 valves)	9	33.1	5.40	4.3(10 ⁷)	1.1(10 ⁷)	1.78
	27	54.7	6.85	5.8(10 ⁷)	1.1(10 ⁷)	1.69
	36	66.8	7.70	6.4(10 ⁷)	1.1(10 ⁷)	1.72

Avg = 1.73

(Continued)

Operation	Test	Lift ft	T min	R		k_t
				Max	@ T	
Filling (1 valve)	15	39.1	10.40	5.5(10 ⁷)	1.1(10 ⁷)	1.39
	35	66.8	13.80	7.4(10 ⁷)	1.1(10 ⁷)	1.38

Avg = 1.39

Prototype (method 3)

20. Prototype values of dz/dt (data channel LWS2) are shown in Figures A4 (2-valve filling) and A5 (1-valve filling). The least-mean-square best-fit linear equations for each test are also shown in the figures. The resulting evaluations of k_t , using Equations A9 and A10(b), are as follows:

Condition	Test	Lift ft	d^2z/dt^2	k_t
			ft/sec ²	
Filling (2 valves)	9	33.1	-.0006007	1.52
	17	43.4	-.0005376	1.69
	23	48.7	-.0005391	1.69
	27	54.7	-.0005438	1.67
	34	63.0	-.0005442	1.67
	36	66.8	-.0005284	1.73
				Avg = 1.66
Filling (1 valve)	15	39.1	-.0001697	1.34
	21	43.9	-.0001706	1.33
	35	66.8	-.001797	1.27
				Avg = 1.31

Distribution of Losses in the System

Entrance loss

21. Here, and in subsequent paragraphs, an energy grade line (EGL) elevation is simply the sum of the piezometric head elevation, h , and the average velocity head, h_v , at the location of interest. The loss (H_{L1} is the entrance loss) is the difference in EGL elevations as previously shown in Figure A2. Prototype instrumentation locations are not appropriate for separation of intake losses from conduit losses.

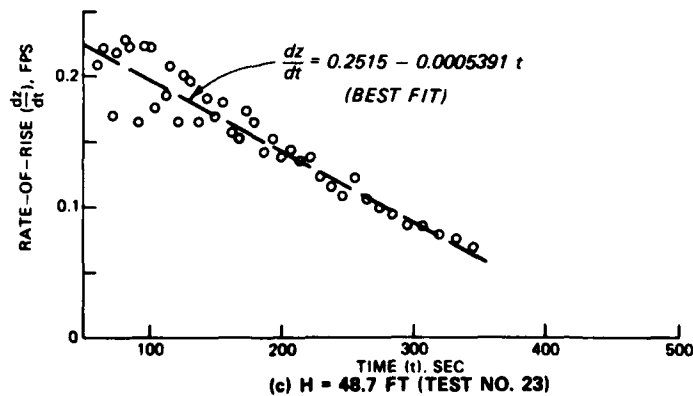
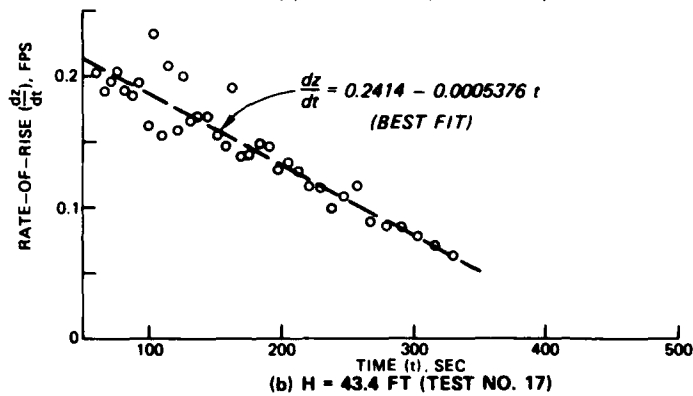
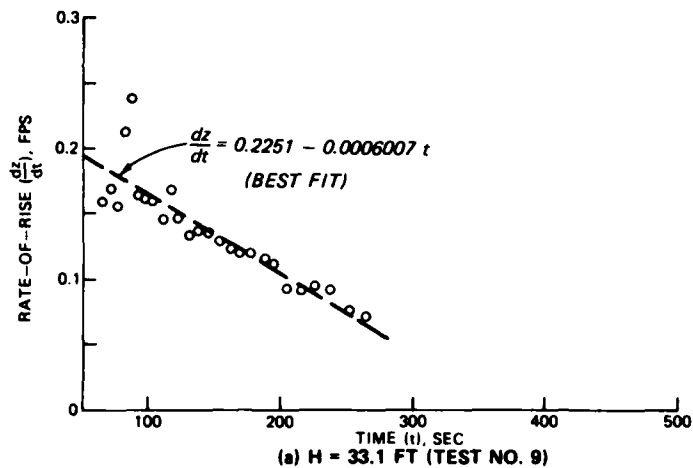
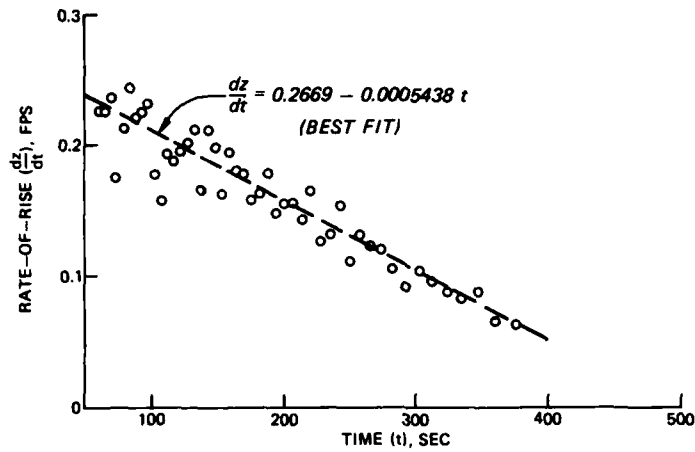
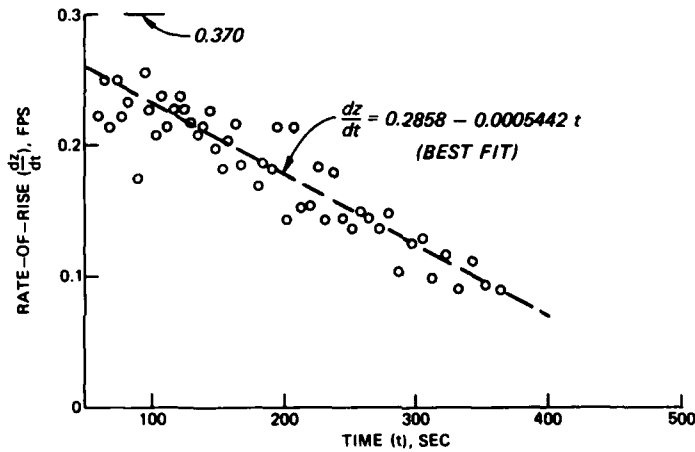


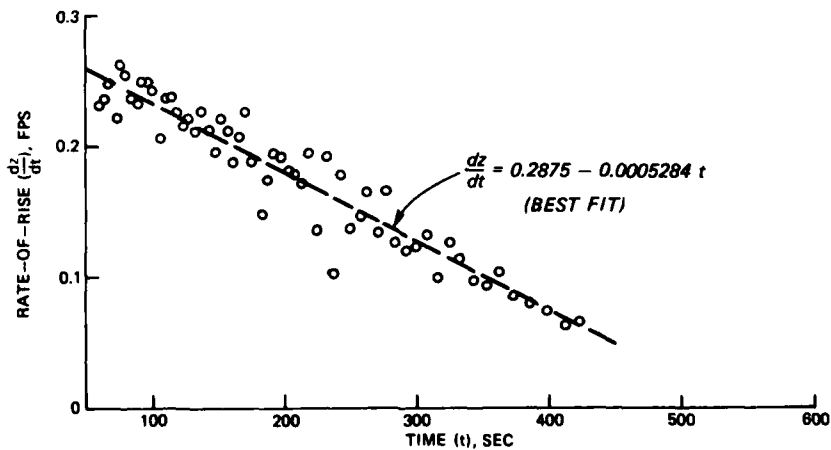
Figure A4. Rate-of-rise (two-valve filling; prototype)
(sheet 1 of 2)



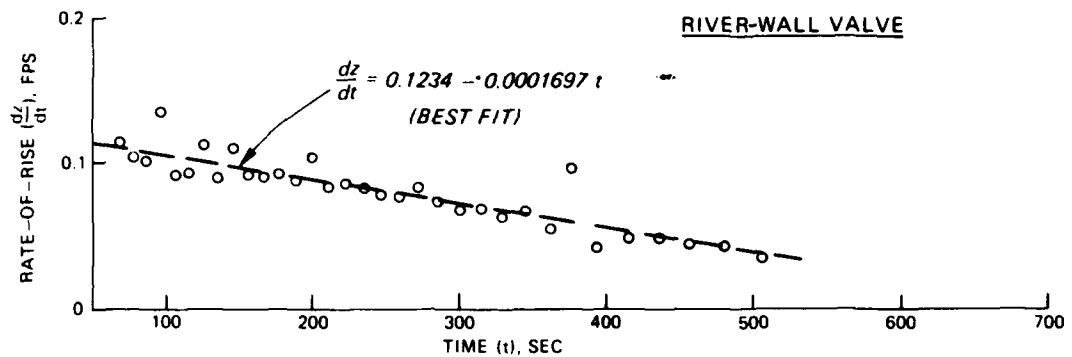
(d) $H = 54.7$ FT (TEST NO. 27)



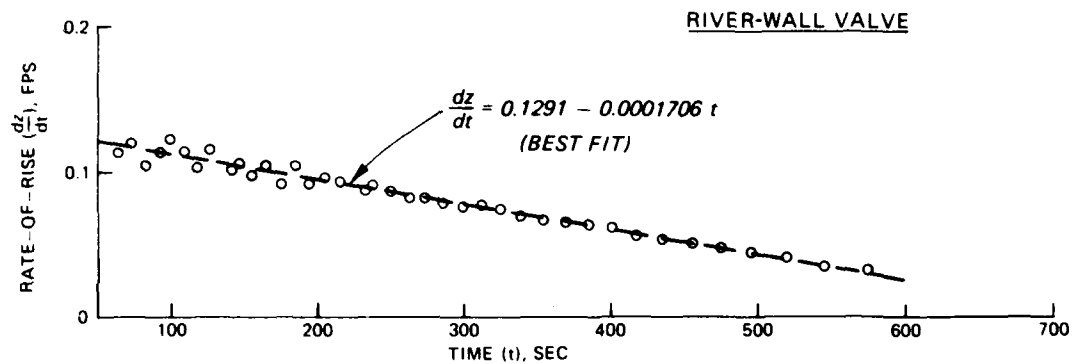
(e) $H = 83.0$ FT (TEST NO. 34)



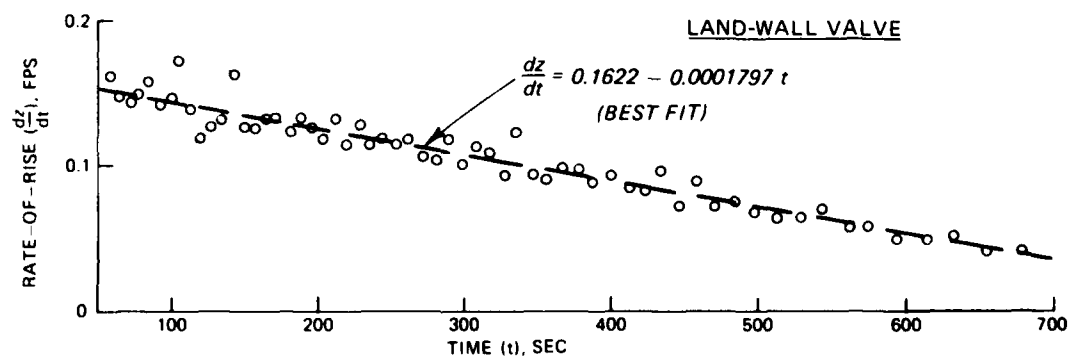
(f) $H = 86.8$ FT (TEST NO. 36)



(a) H = 39.1 FT (TEST NO. 15)



(b) H = 43.9 FT (TEST NO. 21)



(c) H = 66.8 FT (TEST NO. 35)

Figure A5. Rate-of-rise (one-valve filling; prototype)

The model evaluations (using intake piezometer 19) are as follows:

Condition	$\frac{h}{ft}$	$\frac{h_v}{ft}$	$\frac{H_{L1}}{ft}$	$\frac{V^2}{2g}$	k_1
1. Original design (2 valves)	234.2	16.8	3.0	23.9	0.13
2. Type 20 design (2 valves)	230.7	18.6	5.7	26.4	0.22
3. Type 20 design (1 valve)	219.3	30.1	5.6	42.8	0.13

Avg (Type 20) = 0.18

Valve loss (valve fully open)

22. The value of k_v for valve fully open is small and nominally taken equal to 0.10--this value is adopted and used herein.

Exit losses

23. The exit for a filling test is the floor culvert manifold; the expected exit loss, H_{L4} , equals one velocity head at the ports which, when converted to the reference velocity, results in

$$k_{L4} = \left(\frac{A_c}{A_p} \right)^2 \quad (A12)$$

in which A_p is the total port area divided by the number (n) of valves operated. Equation A12 is a reference condition to which the experimental values of k_{L4} are compared.

24. The evaluation of k_{L4} from model and prototype test data is given in the following table (prototype scale) and the comparison is shown in Figure A6. As expected, the model and prototype k_{L4} values are in reasonable agreement--ranging from 15 to 47 percent greater than the values obtained from Equation A12.

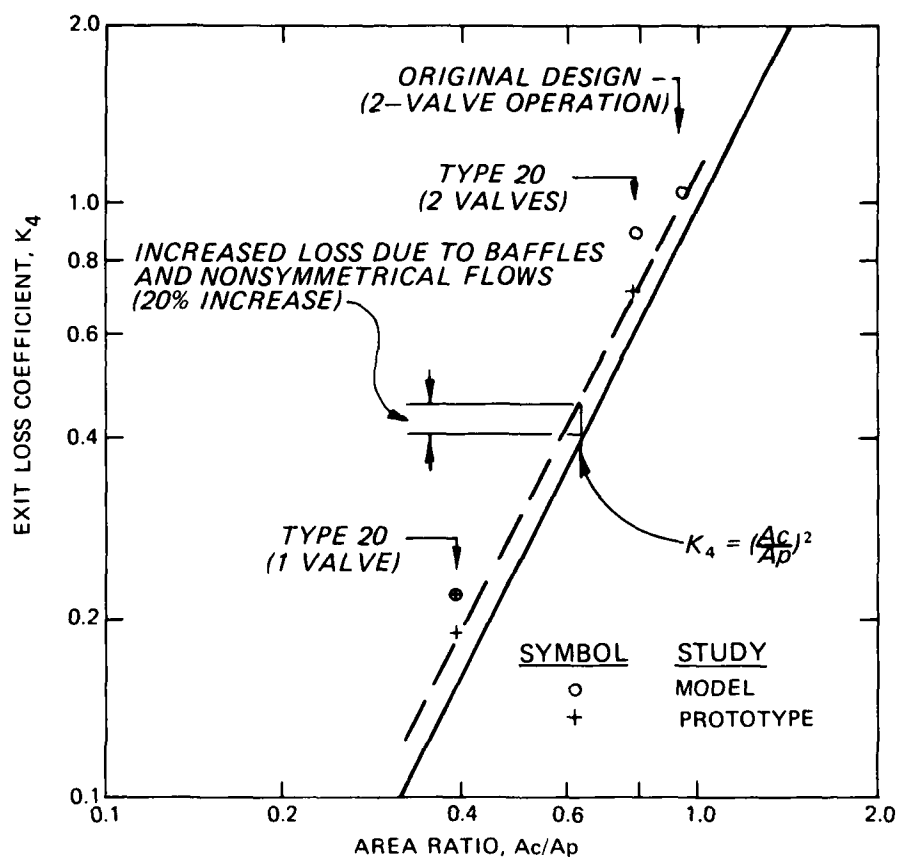


Figure A6. Exit loss coefficient

Condition	(A_c/A_p) (A_c^2/A_p^2)	Piezometer	h ft	h_v ft	EGL ft	H_{L4} ft	$v^2/2g$ ft	k_4
1. Model-- steady flow, original design	0.93	8, 10,	222.3	0	222.3			
	(0.87)	7, 9	213.0	10.8	223.8			
				Avg =	223.1	25.1	23.9	1.05
2. Model-- 2 valves type 20 culvert (90 sec)	0.78	8, 10	221.3	0	221.3			
	(0.61)	7, 9	207.9	16.2	224.1			
				Avg =	222.7	23.4	26.4	0.89

(Continued)

Condition	(A_c/A_p) (A_c^2/A_p^2)	Piezometer	h ft	h_v ft	EGL ft	H_{L4} ft	$V^2/2g$ ft	k_4
3. Model-- 1 valve type 20 culvert (90 sec)	0.39 (0.15)	8, 10 7, 9	203.8 196.1	0 6.6	203.8 202.7			
				Avg =	203.2	9.5	42.8	0.22
4. Prototype-- 2 valves test 34 (80 sec)	0.78 (0.61)	TL4, TL5 TL2, TL3	220.4 207.6	0 19.4	220.4 227.0			
				Avg =	223.7	22.0	31.6	0.70
5. Prototype-- R/W valve test 21 (80 sec)	0.39 (0.15)	TL4, TL5, TL2, TL3	220.7 216.5	0 4.5	220.7 221.0			
				Avg =	220.9	5.6	29.4	0.19
6. Prototype-- L/W valve test 35 (80 sec)	0.39 (0.15)	TL4, TL5, TL2, TL3	204.1 195.9	0 7.3	204.1 203.2			
				Avg =	203.7	10.3	47.6	0.22

Conduit losses

25. These losses are made up of effects due to form and to hydraulic friction; for this discussion the hydraulic friction is taken from the smooth boundary relation

$$\frac{1}{\sqrt{f}} = 2 \log R \sqrt{f} \quad (A13)$$

and re-formed so that

$$k_{2s} + k_{3s} = \frac{fL_1}{D_1} \left[1 + \left(\frac{D_1}{D_2} \right)^5 \frac{L_2}{L_1} \alpha_2^2 \right] = 42.9 f \quad (A14)$$

where

f = friction factor

$k_{2s} + k_{3s}$ = that part of $k_2 + k_3$ that is Reynolds number dependent

D_1, D_2, L_1, L_2 = culvert segment geometry (paragraph 14)

Overall loss coefficient and $k_{2s} + k_{3s}$ from Equations A13 and A14 shown in Figure A7. The following tabulation shows the loss

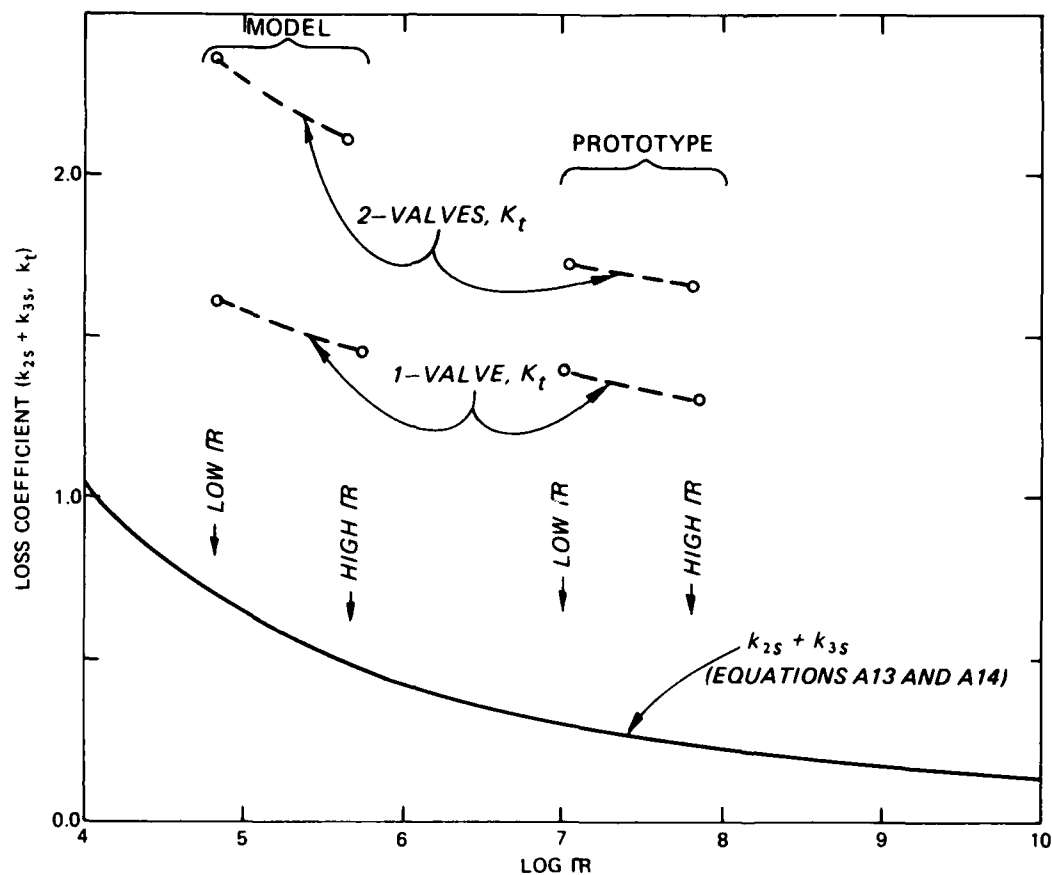


Figure A7. Variation in head loss coefficients as a function of Reynolds number

coefficient divisions--the remnant, $k_{2F} + k_{3F}$, should, primarily, be form-dependent.

Condition	Model (M) or Proto- type (P)	R	k_t	$k_{2s} + k_{3s}$	k_l	k_v	k_4	$k_{2F} + k_{3F}$
2 valves	P	High	1.66	0.24	0.18	0.10	0.70	0.44
	P	Low	1.73	0.30	0.18	0.10	0.70	0.45
	M	High	2.11	0.49	0.18	0.10	0.89	0.45
	M	Low	2.37	0.70	0.18	0.10	0.89	0.50

(Continued)

Condition	Model (M) or Proto- type (P)	R	k_t	$k_{2s} + k_{3s}$	k_1	k_v	k_4	$k_{2F} + k_{3F}$
1 valve	P	High	1.31	0.24	0.18	0.10	0.21	0.58
	P	Low	1.39	0.30	0.18	0.10	0.21	0.60
	M	High	1.45	0.47	0.18	0.10	0.22	0.48
	M	Low	1.61	0.69	0.18	0.10	0.22	0.42

26. The total conduit loss is taken simply as the sum, $k_2 + k_3 = k_{2s} + k_{3s} + k_{2F} + k_{3F}$, and average values of $k_{2F} + k_{3F}$ as best estimates of the form loss (0.46 and 0.54 for 2-valve and 1-valve operation, respectively). The subdivision into upstream and downstream losses requires an EGL measurement immediately upstream of the valve; since the valve well water surface is often of interest, this level (not presented in the model report; $k_1 + k_2 = 0.40$ in Bankhead prototype) is suggested as the required piezometric head measurement. Since k_1 and the sum $k_1 + k_2$ are known, the values of k_2 and k_3 can be calculated sequentially; i.e., the proportion of the Reynolds losses is known from Equation A14.

Summary

27. For solutions involving numerical integration with $k_t =$ constant, the following values apply:

Condition	M or P	k_1	k_{2s}	k_{2F}	k_2	k_{3s}	k_{3F}	k_3	k_v	k_4	k_t
2 valves	P	0.18	0.14	0.08	0.22	0.16	0.38	0.54	0.10	0.70	1.74
	M	0.18	0.33	0.08	0.41	0.37	0.38	0.75	0.10	0.89	2.33
1 valve	P	0.18	0.14	0.08	0.22	0.16	0.46	0.62	0.10	0.21	1.33
	M	0.18	0.32	0.08	0.40	0.37	0.46	0.83	0.10	0.22	1.73

28. In setting up Equations A2 and A7, C_L is a discharge coefficient and k_t a loss coefficient; if both equations are accurate representations of the flow, then $C_L^2 k_t = 1.00$. The values of $C_L^2 k_t$ for the above four filling situations are:

<u>Condition</u>	<u>M or P</u>	$\frac{C_L^2 k_t}{L}$
2 valves	P	1.03
	M	1.05
1 valve	P	1.05
	M	1.05

Overtravel

29. Overtravel (prototype dimensions) is evaluated by means of Equation All(a),

<u>Condition</u>	<u>M or P</u>	<u>Equation All(a)</u>			<u>d_o , ft</u>
		<u>L_m , ft</u>	<u>k_t</u>	<u>d_o , ft</u>	<u>Observed</u>
2 valves	P	549	1.74	1.68	1.1-1.5
	M	549	2.32	1.26	1.1
1 valve	P	549	1.33	1.10	0.7
	M	549	1.72	0.85	--

Conclusions and Recommendations

30. Neither the model nor the prototype instrumentation was set up to provide the complete information sets required for the model-prototype comparison outlined herein. As a consequence, uncertainties still exist regarding the extrapolation of some specific losses (k_1 for example). On the other hand, the comparisons are encouraging with regard, first, to the basic applicability of the analysis to the model and to the prototype lock and, second, to the suggested method of handling friction losses. The following recommendations are concerned with future test programs.

- a. Steady-flow valve-full-open model tests, for separating friction and form effects, are required. These should use several lifts ranging from a low value (approximately equal to the overtravel) to the design lift. Key measurements are the lift and the flow rate for overall losses and piezometric head values near the intake, outlet, and valve well (along with the water surface in the well) for loss distributions.

- b. The outlet loss, k_4 , is larger (as calculated herein) in the model than in the prototype. This may be due simply to measurement inaccuracies or to the small geometrical differences between the model and the prototype outlets; on the other hand, the difference could be attributed to the presence or absence of a tow in the chamber. This rather minor item should also be resolved by means of steady-flow tests (high lifts) in a hydraulic model.
- c. The numerical integration procedure (Reference R3) should be extended to include, at least, the following items:
- (1) Two culverts not of the same geometry
 - (2) Unsteady effects evaluated separately for the culverts upstream and downstream of the valves
 - (3) Some variation in friction loss during a lock operation.

31. Valve effects were excluded from this appendix inasmuch as both model and prototype data are inadequate as far as accurately evaluating valve hydraulic characteristics. For this reason, in future model studies at least one steady-flow experiment should be performed with the valve partially open; key measurements would be lift (high), flow rate, valve opening (35 to 60 percent open), and piezometric head at the culvert roof immediately downstream from the valves.

32. The standard unsteady-flow lock test has proven to be an effective design aid as far as the overall complex flow phenomena are concerned; on the other hand, whenever accurate pressure predictions are required within the prototype culverts (as in the new high-lift locks, for example), then additional laboratory testing and analysis are obviously required.

APPENDIX B: NOTATION

A	Area
A_c	Cross-sectional area of the filling culvert downstream
A_L	Chamber surface area, 73,700 ft ²
A_p	Total emptying port area
A_p/A_c	Port-to-culvert area ratio
b	Vertical valve opening
B	Height of culvert downstream
C_c	Contraction coefficient
C_L	Overall lock coefficient
d_o	Overtravel, ft
D_1, D_2	Equivalent diameter of the culvert segments
f	Friction factor
g	Acceleration due to gravity
H	Initial head, ft; i.e., lift
H_L	Head loss coefficient
H_{Lt}	Overall loss
H_m	Overall inertial effect
K	Overall valve coefficient
k_t	Overall loss coefficient
k_1, k_2, k_3, k_4	Loss coefficients
K_L	Manifold loss coefficient
K_v	Valve loss coefficient
L	Length dimension
L_m	Inertial length coefficient
n	Number of valves used (1 or 2)
p_1	Piezometric head elevation at valve well (UVW)
p_2	Piezometric head elevation downstream of valve (TV1)
Q	Discharge from math model
R	Reynolds number
T	Lock filling time, sec
t_v	Valve time, sec
V	Reference velocity

V_c	Mean culvert velocity
w	Width of culvert downstream of valve
y	Chart trace displacement
Z_u	Upper pool elevation
α	Flow ratio
β	Angle of the gate lip with the horizontal
Δh	Difference in piezometric head between two locations in the culvert
γ	Unit weight of fluid (water)
ν	Kinematic viscosity

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Tool, Allen R

Prototype filling and emptying system measurements, New Bankhead Lock, Black Warrior River, Alabama / by Allen R. Tool. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.

34, [27] p., 12 leaves of plates : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; HL-80-13)

Prepared for U. S. Army Engineer District, Mobile, Mobile, Ala.

1. Hydraulic models. 2. John Hollis Bankhead Lock. 3. Lock filling and emptying systems. 4. Locks (Waterways). 5. Prototype tests. 6. Prototypes. 7. Water pressure measurement. I. United States. Army. Corps of Engineers. Mobile District. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; HL-80-13.
TA7.W34 no.HL-80-13

